PB90-108846

Evaluation of Internally Staged Coal Burners and Sorbent Jet Aerodynamics for Combined SO2/NOx Control in Utility Boilers. Volume 2. Testing in a 100 Million Btu/hr Experimental Furnace

Energy and Environmental Research Corp., Irvine, CA

Prepared for:

Environmental Protection Agency, Research Triangle Park, NC

Sep 89

U.S. Department of Commerce
National Technical Information Service
NTIS

PB90-108846

EPA-600/7-89-009
September 1989

EVALUATION OF INTERNALLY STAGED COAL BURNERS AND SORBENT JET AERODYNAMICS FOR COMBINED SO_2/NO_x CONTROL IN UTILITY BOILERS

Volume 2. Testing in a 100 Million Btu/hr Experimental Furnace

by

B. M. Cetegen
J. Clough
G. C. England
T. R. Johnson
Y. Kwan
R. Payne

Energy and Environmental Research Corporation
18 Mason
Irvine, California 92718-2798

EPA Contract 68-02-3923

EPA Project Officer: D. Bruce Henschel
Air and Energy Engineering Research Laboratory
Office of Environmental Engineering and Technology Demonstration
Research Triangle Park, NC 27711

AIR AND ENERGY ENGINEERING RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC 27711

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NATIONAL TECHNICAL INFORMATION SERVICE
SPRINGFIELD, VA. 22161

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1-A

ABSTRACT

As part of EPA's Limestone Injection/Multistage Burner (LIMB) program, testing was conducted on a 100 million Btu/hr coal-fired experimental furnace. The primary objective was to explore the potential for achieving effective SO_2 removal using calcium-based sorbents, through appropriate selection of injection location and injector design and operating parameters. To obtain simultaneous reductions of SO_2 and NO_x, the sorbent testing was conducted with the furnace operating with an internally staged low-NO_x burner, which was designed to accomplish fuel/air staging internally within the burner. Such internal staging is intended to avoid the need for external tertiary air ports, and thus simplify the retrofit of such a low-NO_x burner into existing pre-NSPS utility furnaces. The testing reported here was a follow-on to testing on a smaller scale (10 million Btu/hr), reported previously in Reference 1.

Because the emphasis of this testing was on improving sorbent performance, the testing of options for reducing NO_x emissions from the burner by internal staging was limited. The options tested were limited to two coal splitters (referred to as the T-15 and T-30 splitters), designed to divide the coal stream into four initially fuel-rich flames. The best set of conditions (the T-30 splitter with low swirl in the secondary air) resulted in NO_x emissions of 550 ppm (dry, 0% O_2), compared to 830-900 ppm from the baseline unstaged burner, a reduction of about 35 percent (less than the 50-60 percent desired). Flame length from the staged burner was acceptable (22 ft), and CO was less than 40 ppm. Additional NO_x reductions might have been achieved had additional staging approaches (e.g., divided secondary air registers) also been tested.

Variables addressed during the SO_2 sorbent testing included: injection location (three locations on the front wall, one on the rear wall); injection velocity; injector diameter; number of injectors; and injector design (single-pipe vs. double-concentric jets). Three sorbents were tested. With the recirculation patterns created in the furnace by the burner, reasonable SO_2 removals could be achieved only under the following two conditions: injection from the rear wall at an optimum velocity, to avoid the sorbent's penetrating into the recirculation zone while at the same time getting adequate dispersion in the exhaust flow; and injection high on the front wall (19 ft above the burner), using large jets having sufficient momentum to penetrate through the recirculation zone into the furnace exhaust flow. At a calcium-to-sulfur molar ratio of 2, SO_2 removals under these injection conditions were: 30-40 percent with Vicron 45-3 limestone (10 micrometers mass mean); 45-50 percent with D3002 dolomite (12 micrometers); and 58-62 percent with Type-S pressure-hydrated dolomitic lime (1.4 micrometers).

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TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-89-009

2\.

3. RECIPIENT'S ACCESSION NO.

4. TITLE AND SUBTITLE Evaluation of Internally Staged Coal Burners and Sorbent Jet Aerodynamics for Combined SO_2/NO_x Control in Utility Boilers; Volume 2. Testing in a 100 Million Btu/Hr Experimental Furnace

5. REPORT DATE September 1989

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S) B. M. Cetegen, J. Clough, G. C. England, T. R. Johnson, Y. Kwan, and R. Payne

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Energy and Environmental Research Corporation
18 Mason
Irvine, California 92718-2798

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO. 68-02-3923

12. SPONSORING AGENCY NAME AND ADDRESS
EPA, Office of Research and Development
Air and Energy Engineering Research Laboratory
Research Triangle Park, NC 27711

13. TYPE OF REPORT AND PERIOD COVERED Final; 11/84 - 6/85

14. SPONSORING AGENCY CODE **EPA/600/13**

15. SUPPLEMENTARY NOTES AEERL project officer is D. Bruce Henschel, Mail Drop 54, 919/541-4112. Volume 1, tests on a smaller scale, is EPA-600/7-89-007.

16. ABSTRACT

The report gives results of tests on a 100 million Btu/hr (29 MWt) experimental furnace to explore methods for achieving effective SO2 removal in a coal-fired utility boiler using calcium-based sorbents, through appropriate selection of injection location and injector design/operating parameters. Methods were also tested to reduce NOx emissions from the coal burners without external air ports (i.e., with internal fuel/air staging). Sorbent jet testing showed that, through cold modelling, injection locations and velocities could be selected which avoided recirculation of the sorbent into the burner zone (hence dead-burning). At the best conditions, SO2 removals at Ca/S = 2 were 30-40% with finely ground limestone, 45-50% with dolomite, and 60% with pressure-hydrated dolomitic lime. Limited testing of burner modifications to achieve internal staging resulted in about a 35% reduction in NOx, through use of coal splitters.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Sorbents	Pollution Control	13B	11G
Coal	Limestone	Stationary Sources	21D	08G
Combustion	Calcium Oxides	Internal Staging	21B	
Utilities	Dolomite	Utility Boilers	13A	
Boilers	Nitrogen Oxides			
Sulfur Dioxide	Jets		07B	20D
	Aerodynamics			

18. DISTRIBUTION STATEMENT **Release to Public**

19. SECURITY CLASS *(This Report)* **Unclassified**

20. SECURITY CLASS *(This page)* **Unclassified**

21. NO. OF PAGES 131

22. PRICE A07

EPA Form 2220-1 (9-73)

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METRIC CONVERSION FACTORS

Although it is EPA's policy to use metric units in its documents, non-metric units have been used in this report consistent with common practice in the furnace design field. Readers more accustomed to the metric system may use the following factors to convert to that system.

Non-Metric	Times	Yields metric
degrees Fahrenheit (°F)	5/9 (°F - 32)	degrees Centigrade (°C)
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.305	meter (m)
foot per second (ft/s)	0.305	meter per second (m/s)
10^6 British thermal units per hour (10^6 Btu/hr)	0.293	megawatts (MW) thermal
cubic feet per minute (ft^3/min)	0.47	liters per second (L/s)

1.0 INTRODUCTION

1.1 General Project Description

The Limestone Injection/Multistage Burner (LIMB) program is designed to develop technology which can achieve moderate (50-60%) reductions in both SO_2 and NO_x emissions from electric utility boilers, through the use of calcium-based SO_2 sorbents (such as limestone) and the use of staged burners. LIMB technology is intended to be relatively easy to retrofit into existing boilers as part of an acid rain control strategy.

As part of EPA's LIMB development program, an experimental project was undertaken to assess possible designs for staged, low-NO_x burners which could achieve the desired air/fuel staging internal to the burner (i.e., without external tertiary air ports). As part of this study, an extensive evaluation was made of sorbent jet aerodynamics, in an effort to identify sorbent jet design/ operating parameters which would provide optimum SO_2 capture in conjunction with the internally-staged burner.

The experimental work on this project was conducted in two phases. The first phase involved testing in a 10 million Btu/hr experimental furnace referred to as the Small Watertube Simulator (SWS). This SWS testing was described in an earlier report (1). The second phase involved testing in an experimental furnace referred to as the Large Watertube Simulator (LWS), operating with a burner sized at 100 million Btu/hr (near full scale for a single burner). The LWS testing was intended to explore and confirm some of the more promising sorbent injection alternatives, and some of the more promising internally-staged burner design features, identified during the testing at the smaller scale. The LWS phase of the testing is described in this current report.

1.2 Background on Sorbent Injection for SO_2 Control

Sulfur capture by the injection of calcium-based sorbents into furnaces involves three simultaneous processes -- calcination, deactivation and sulfation.

- Calcination occurs when the raw sorbent is heated, and the calcium carbonate (and magnesium carbonate) in the sorbent particles are converted to calcium oxide (and magnesium oxide) with high surface area. This is the step which develops the sorbent's activity for sulfur capture. Sorbent activity increases with increasing surface area, and appears to be mainly a function of peak particle temperature.

- Deactivation occurs through loss of surface area due to crystal growth and sintering. Deactivation can also occur due to sorbent interaction with minerals in the coal ash at high temperatures. The sintering process occurs rapidly at high temperatures; sorbent reactivity can be seriously reduced if the sorbent is held at high temperature for any length of time. The effective reactivity of a sorbent at a given temperature is thus determined by the competing effects of calcination (reactivity development) and deactivation.

- Sulfation is normally represented by the reaction:

  $$CaO + SO_2 + 1/2\ O_2 \longrightarrow CaSO_4$$

  Sulfation occurs on the surface of the sorbent particle; as the reaction proceeds, a product layer of calcium sulfate is formed. The sulfation reaction rate is controlled by the combined resistances of diffusion and surface reactions, and is strongly temperature dependent.

Calcium sulfate is unstable at temperatures above approximately 2250 °F. Below about 1750 °F, the rate of the sulfation reaction is significantly reduced. This thermodynamic "ceiling" and this chemical kinetics "floor" define what is commonly referred to as the "sulfation window", with an upper temperature limit of 2250 °F and a lower limit of about 1750 °F. An additional consideration defining the upper limit is that, at high temperatures, sorbent deactivation due to sintering will become increasingly severe.

During the sorbent jet testing in this project, consideration was given to:

- injection locations near the burner. Near-burner injection provides the most effective sorbent dispersion (due to rapid mixing in the burner zone) and the maximum sorbent residence time at sulfation temperatures (by ensuring that the sorbent is well dispersed in time to "see" the entire sulfation window). However, near-burner injection can cause sorbent deactivation, due to exposure to high temperatures and to coal ash minerals in the flame zone.
- injection remote from the burner. Remote injection reduces deactivation of the sorbent by injecting at a lower temperature, but necessitates care in achieving good dispersion and adequate sorbent residence time.

Because of the potential benefits of near-burner injection, if deactivation could be avoided, a significant portion of the SWS testing (1) investigated furnace conditions and sorbent jet parameters which might be applicable to near-burner injection. A portion of the LWS testing reported here also considered near-burner injection, but the primary focus of the LWS phase of this project was on injection remote from the burners.

In utility boiler furnaces, gas temperature usually falls to the 2250 °F level in the upper furnace region, close to the furnace exit. Thus, remote injection involves injection into this upper furnace region of a boiler. Because mixing and dispersion of the sorbent is more difficult in this region, compared to the burner region, an injection scheme is needed that gives rapid and adequate dispersion. Sorbent injection in the upper furnace is achieved by turbulent jets, usually injected at right angles from the furnace walls in cross flow to the gas. Injection parameters such as jet diameter, jet velocity and number of jets will affect the penetration and mixing of the sorbent into the flue gas, affecting overall SO_2 capture.

The LWS was selected for this testing because it was the largest available pilot furnace, with a geometric configuration/flow pattern intended to resemble commercial units. Insulation was added to the LWS so that the sulfation temperature window would be in the appropriate location, in the upper region of the experimental furnace. The 100 x 10^6 Btu/hr burner used in the LWS during this testing included an internally-staged design, based in part on the findings of the low-NO_x burner investigations described Reference 1. This internally-staged burner, simulating a retrofit situation, fulfilled the intent of testing a combined low-SO_2/low-NO_x internally-staged system.

The primary objective of the LWS testing was to study the influence of injection system design parameters on SO_2 capture under conditions which simulated upper-furnace injection. That is, it was desired to identify injection parameters which would provide adequate dispersion of the sorbent over the entire furnace gas in the shortest possible time, and would protect the sorbent from excessive temperatures that might damage its reactivity. The parameters investigated were: the location of the jets in relation to the sulfation temperature window; the location of the jets in relation to the furnace gas flow patterns (i.e., around the perimeter of the furnace); the number of jets; jet diameter; jet velocity; and jet configuration (i.e., single-pipe jets vs. double concentric jets, in which the sorbent jets is surrounded by a larger annular air jet). Also, three different types of calcium-based sorbent were tested, to assess the degree to which jet design is sensitive to sorbent type.

The injection systems tested were all based on jets issuing from the walls of the furnace as jets in cross-flow. As a jet issues from the wall, it begins to entrain the surrounding furnace gas; in so doing, it acquires momentum in the direction of the cross-flow and is bent in that direction. A number of investigators have studied the paths of jets in crossflow, and defined the jet trajectory in terms a correlation involving the jet diameter and the jet-to-stream momentum flux ratio. The correlation of Patrick (2) is typical:

$$\frac{y}{d} = J^{.43} \left(\frac{x}{d}\right)^{.38}$$

where y is cross stream penetration of the jet
x is the downstream distance of the jet
d is jet diameter

J is jet-to-stream momentum flux ratio, $J = \dfrac{\rho_j V_j^2}{\rho_s V_s^2}$
ρ_j is jet density
ρ_s is cross-stream density
V_j is jet velocity
V_s is cross stream velocity

Thus the path of the jet and hence its cross-stream penetration depends upon the jet diameter and the jet velocity relative to the cross-stream velocity. Increasing the jet velocity or the jet diameter will increase the overall jet penetration.

For a given total sorbent-plus-carrier-air flow rate, any desired penetration can be obtained by selection of an appropriate combination of the number of jets, the jet diameter and jet velocity. In designing a jet injection scheme, it usually will be possible to select several combinations of these parameters that will give acceptable penetration, so other criteria will be needed to identify optimum injection schemes, such as the rate of mixing of each individual jet which also is affected by velocity and diameter. Also, the gas flow conditions in the upper furnace region are not uniform, and there is thus uncertainty about the true path of jets in these conditions. Therefore -- although the general principles for the design of an injection system are understood -- one cannot predict with confidence the way in which the various choices of injection parameters might affect jet mixing and dispersion and overall SO_2 capture.

1.3 Background on Internally-Staged Low-NO_x Burners

Some low-NO_x staged wall burners which have been tested involve the use of outboard tertiary air ports -- external to the burner throat -- in order to achieve air/fuel staging. In some cases, such external ports could prove difficult to retrofit into an existing boiler originally designed for a pre-NSPS burner; additional tube bends would be required to accommodate the ports (of potential concern when the boiler is top-supported), and the ports could interfere with buckstays, windbox trusses and other structural constraints surrounding the original burners. An objective of this project was to investigate wall burner design approaches which could effectively achieve air and/or fuel staging without external ports -- i.e., by modifications internal to the burner, in a manner which would facilitate retrofit. In this report, burners with such modifications are referred to as internally-staged burners.

In the testing on the SWS (1), a substantial effort was devoted to testing alternative burner design approaches to effectively achieve internal staging. In the LWS testing, the low-NO_x internally-staged burner testing was limited to testing of the two coal nozzle designs (15° and 30° "T-series" coal splitters) which appeared from the SWS tests to give the best NO_x reduction results.

2.0 EXPERIMENTAL SYSTEMS

This section describes the equipment and hardware which was utilized for the pilot-scale tests in the LWS furnace.

- Burner Designs
- Test Facilities
- Fuel and Sorbents

2.1 Burner Designs

For these investigations, the LWS was fired with a single burner designed for a firing rate of 100 x 10^6 Btu/hr. This burner, designated the IS-100 burner, was based on an unstaged, high NO_x burner, typical of pre-NSPS commercial burners. Two different versions of the IS-100 burner design were fabricated and tested for this phase of the program, namely:

- IS-100 - Annular Coal Nozzle Design (unstaged, high NO_x)
- IS-100 - Axial Coal Nozzle Design (some staging)

The annular coal nozzle design resembles a pre-NSPS commercial, high turbulence burner, incorporating no attempts to achieve fuel or air staging. The axial coal nozzle was designed to include two different coal splitter inserts which had given the best NO_x reductions during the testing of internal staging alternatives on the SWS (1). Table 2-1 lists some of the key dimensions and operating characteristics of these burners.

Since the primary focus of the LWS testing was to assess sorbent jet parameters, the testing of internally-staged low-NO_x burners was limited to the consideration of the two coal splitters in the axial coal nozzle design.

TABLE 2-1. CHARACTERISTICS OF 100 X 10^6 BTU/HR TEST BURNERS

Parameter	IS-100 Annular Burner	IS-100 Axial Burner
Primary Air Design		
Stoichiometric ratio (SR_P) (percent of theoretical air)	20*	18
Primary air velocity (ft/s)	70	80
Diameter of coal/primary air pipe (in.)	18.50	13.75
Diameter of core pipe (in.)	13.75	--
Secondary Air Design		
Stoichiometric ratio (SR_{Sec}) (percent of theoretical air)	100	102
Secondary air velocity (ft/s)	120	105
Diameter of secondary air channel/burner throat (in.)	33	33
Area of annular secondary air channel (ft^2)	4.02	4.81
Design of Burner Exit		
Diameter of burner throat, before quarl (in.)	33	33
Half-angle of quarl (degrees)	25	25
Ratio of quarl depth to throat diameter	0.4	0.4
Overfire Air Design**		
Stoichiometric ratio (SR_{OFA}) (percent of theoretical air)	5**	5**
Overfire air velocity (ft/s)	30	30
Number of OFA ports	4	4
Diameter of OFA ports (in.)	6	6

* For annular burner, primary air stoichiometry includes core air.

** Overfire air was used only when sorbent was injected at Level III using either the 6-inch single-jet configuration or the double concentric jet configuration.

2.1.1 Annular Coal Nozzle Burner

Figure 2-1 shows a cross-sectional view of the unstaged annular coal nozzle burner. Coal and primary air are injected through an annular passage which surrounds a central core pipe. A small portion of combustion air is supplied through the core pipe; this core air provides for cooling of ignition equipment, establishes bluff body recirculation at the base of the flame, and also supplies an additional source of oxygen at the ignition point to improve flame stability. Secondary air is supplied through a single annular nozzle surrounding the coal/primary air pipe. The burner includes only one secondary air passage -- i.e., like typical pre-NSPS burners, the secondary air register is not divided. Swirl is varied in the secondary air with a guide-vane cascade in radial flow. Secondary air swirl level is dictated by the angle of the adjustable swirl vanes. Thus, the swirl level is defined by register setting, as shown in Figure 2-2. A setting of 90 at the register handle represents zero swirl; at this setting, the swirl vanes are at a 90° angle relative to the coal pipe, or wide open, parallel to the air flow. A setting of 15 (i.e., vanes at an angle of 15° relative to the coal pipe) represents the maximum practical swirl position. Although swirl intensity imparted by this register can be increased further by setting the register below the 15 mark, air flow through the burner is severely restricted, and there is a significant pressure drop across the swirl vanes (i.e., the vanes are shut almost all the way).

As indicated in Table 2-1, the secondary air velocity for the annular burner was about 120 ft/s. This is somewhat lower than is typical for pre-NSPS burners (e.g., the secondary air velocity for the HV2 burner tested in the SWS was 190 ft/s), which might be expected to give the annular burner some advantage in reduced NO_x emissions. However, this velocity is well above the 60 ft/s typical for externally-staged distributed mixing burners.

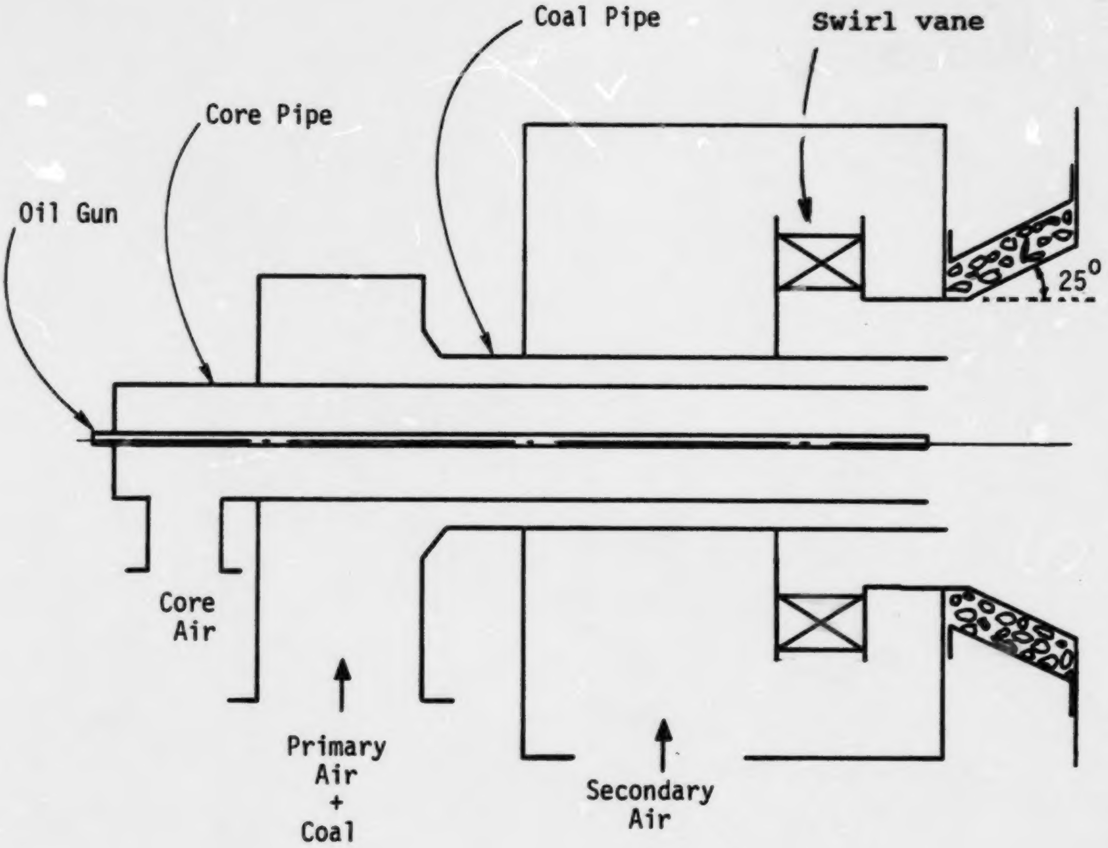
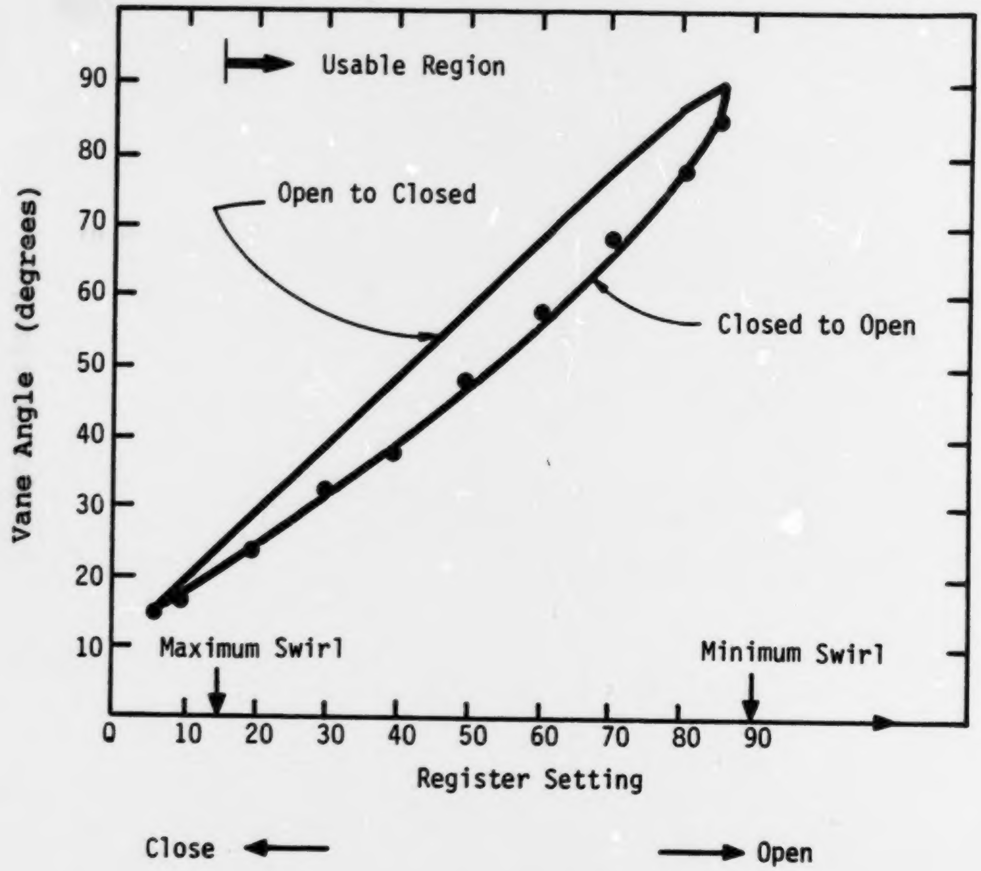

Coal Pipe
Swirl vane
Core Pipe
Oil Gun
25°
Core Air
Primary Air + Coal
Secondary Air

Figure 2-1. IS-100 burner, unstaged annular coal nozzle design.



Note: Vane angle is relative to coal pipe. An angle of 0° indicates vanes closed all the way; an angle of 90° indicates vanes wide open.

Figure 2-2. IS-100 burner - secondary air register characteristics.

In addition to the core air, primary air, and secondary air which are introduced in the burner zone, another stream of air can be introduced into the LWS furnace through the burner wall by a set of four overfire air (OFA) ports equipped with control air dampers. These OFA ports are installed at a location in the upper furnace approximately 19 feet above the burner centerline. In this testing, overfire air was used only when the OFA ports were being used for sorbent injection.

2.1.2 Axial Coal Nozzle Burner

This version of the IS-100 burner, shown in Figure 2-3, consists of a simple axial coal nozzle equipped with a "T-series" coal splitter (Figure 2-4). This particular coal splitter is used in this burner design based upon the results observed in the SWS burner tests described in Reference 1; with conventional coal transport nozzles, the T-series splitters proved to be the most effective of the nozzle modifications tested in reducing NO_x emissions. Other than the use of the coal splitter to achieve some fuel/air staging, the axial burner differs from the annular burner primarily in that the axial burner does not include a central core pipe.

Two T-coal splitters were briefly optimized with the axial burner in the LWS. These two splitters were directly scaled up from the T-15 and T-30 splitters tested in the SWS. The 15 and the 30 refer to the degrees in the angle theta shown in Figure 2-4. It should be noted that because of the shape of the T-splitter, the position of the splitter (with respect to the exit of the coal pipe) will determine the primary air velocity and the trajectory of the coal particles at the exit of the coal nozzle for a given primary air stoichiometric ratio (SR_p). The maximum primary velocity achievable for a given SR_p would be obtained by placing

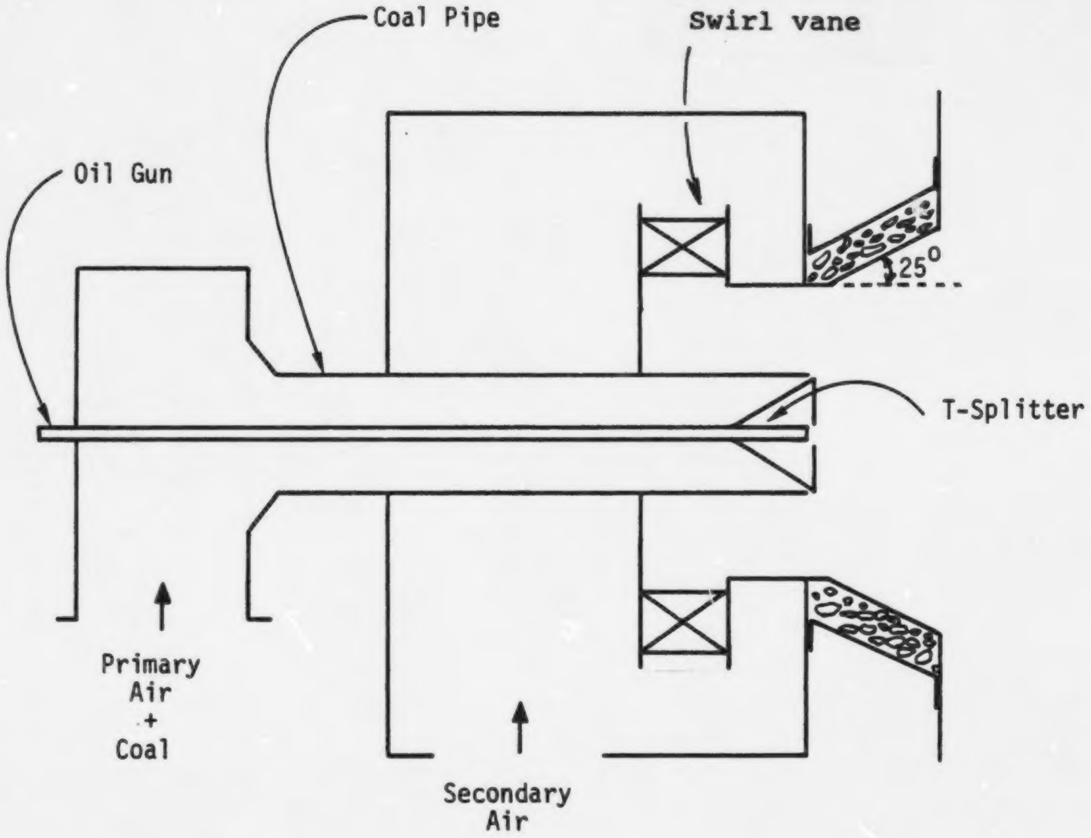

Coal Pipe
Swirl vane
Oil Gun
25°
T-Splitter
Primary Air + Coal
Secondary Air

Figure 2-3. IS-100 burner, staged axial coal nozzle design.

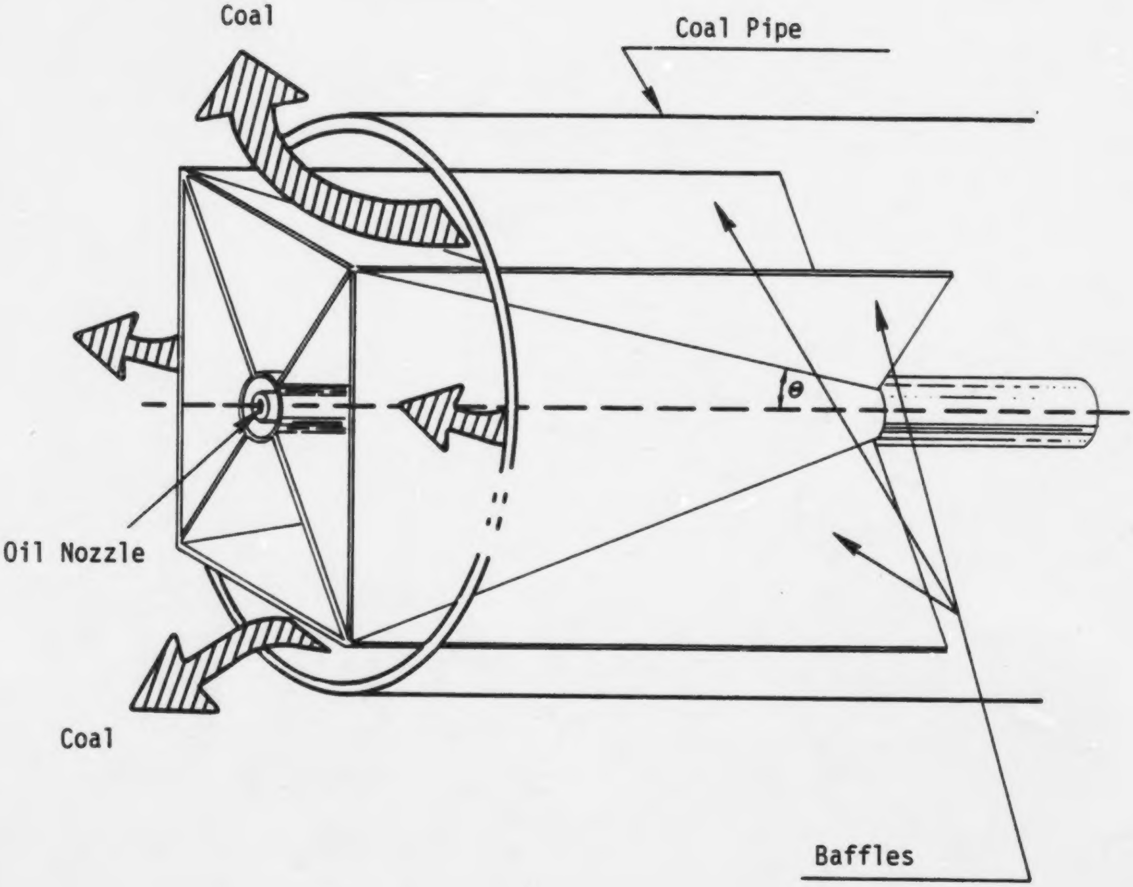

Coal
Coal Pipe
θ
Oil Nozzle
Coal
Baffles

Figure 2-4. Coal splitter (T-series) tested in LWS furnace.

the leading edge of the T-splitter level with the end of the coal nozzle. Pushing the entire splitter forward would result in a minimum primary velocity.

The secondary air register used for this burner is the same undivided register used for the annular coal nozzle, with a single secondary air passage. By comparison, all of the internally-staged burners tested in the SWS had had divided registers, with two (or, in one case, three) secondary air passages. The secondary air velocity in the axial burner was about 105 ft/s, somewhat higher than the 80 ft/s tested for the low-velocity staged burner (LV1) tested in the SWS and the 60 ft/s typical of commercial low-NO_x distributed mixing burners. A lot of effort was not devoted to evaluating internally-staged burner designs in the LWS due to the emphasis of this part of the project on sorbent injection testing. As with the annular burner, air could be introduced through overfire air ports as well as in the burner zone (primary plus secondary).

After initial burner testing and optimization, described in Section 3.1, most of the sorbent injection testing was conducted with the axial coal burner configuration using the T-30 splitter.

2.2 Test Facilities

The burner testing and sorbent injection studies were carried out in the EPA Large Watertube Boiler Simulator (LWS) test facility. This combustor can be fired at heat input rates up to 150 x 10^6 Btu/hr, but was operated at 100 x 10^6 Btu/hr for these tests. The LWS includes the following components:

- Combustor and Combustion Systems
- Sorbent Injection Systems
- Sampling Systems/Measurement and Instrumentation

2.2.1 Combustor Systems

The LWS test facility is illustrated in Figure 2-5. Tables 2-2 and 2-3 list some of the key furnace characteristics. The LWS is a full-scale model of a small wall-fired utility boiler at the Pearl Station of Western Illinois Power Cooperative (WIPCo). It has a maximum firing capacity of 150 x 10^6 Btu/ hr, which is limited only by pulverizer capacity; this is approximately the firing rate of a single full-scale utility burner. The firing depth is 22 feet, which is sufficient to handle burners at the maximum firing rate. It is arranged in front wall firing configuration; the burner is mounted on a removable 10 ft x 10 ft water-cooled panel. To match the thermal environment of typical small utility boilers, the LWS furnace is refractory lined on the vertical surfaces. In the basic configuration, which focuses on matching utility boiler thermal environments in the burner zone, the refractory lining extends from the knuckle up to a height of 16 feet. Additional insulation can be added in the upper furnace region as necessary to match the thermal environment of utility boilers in that region as well. A portion of the hopper is also refractory lined. The furnace is cooled by external water sprays which maintain surface temperatures at controlled levels. The furnace structure is bottom-supported with the hopper below grade. The furnace structure is of unique construction. The walls are corrugated 1/4" Cor-ten steel. Pressure stresses are controlled by buckstays similar to full-scale utility boilers.

In its basic configuration, operating at 100 x 10^6 Btu/hr, the LWS furnace has a quench rate through the sulfation temperature window of approximately 300 F°/sec. The 2250 °F (1500 °K) isotherm, which represents the beginning of the sulfation temperature window, is located well below the LWS nose. A mathematical modeling study of the LWS was conducted to determine how insulation at various

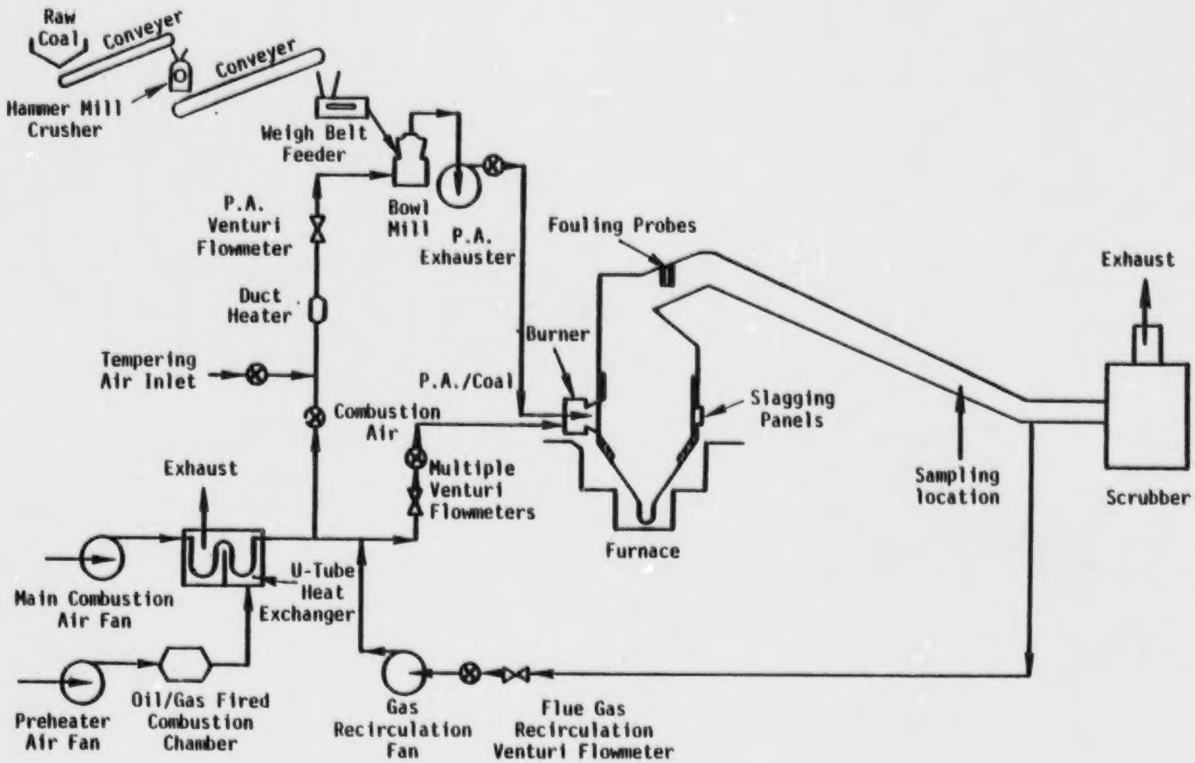

Raw
Coal
Conveyer
Hammer Mill
Crusher
Conveyer
Weigh Belt
Feeder
Bowl
Mill
P.A.
Exhauster
P.A.
Venturi
Flowmeter
Duct
Heater
Tempering
Air Inlet
Combustion
Air
P.A./Coal
Burner
Fouling Probes
Slagging
Panels
Furnace
Sampling
location
Exhaust
Scrubber
Multiple
Venturi
Flowmeters
Exhaust
Main Combustion
Air Fan
U-Tube
Heat
Exchanger
Preheater
Air Fan
Oil/Gas Fired
Combustion
Chamber
Gas
Recirculation
Fan
Flue Gas
Recirculation
Venturi Flowmeter

Figure 2-5. Large Watertube Boiler simulator system schematic.

TABLE 2-2. LWS FURNACE CHARACTERISTICS

Parameter		Value
Firing		
Configuration	Primary	Single Wall
	Optional	Opposed or Corner
Firing Rate	Minimum	50 x 10^6 Btu/hr (Practical Limit)
	Maximum	150 x 10^6 Btu/hr
Dimensions		
Firing depth		22 ft.
Width		16 ft.
Rear Wall Height		20 ft.
Knuckle to Nose Height		27.5 ft.
Nose Angle		37° (from Horizontal)
Hopper Angle		52° (from Horizontal)
Height Above Ground Level		35.7 ft.
Total Vertical Height		50.5 ft (Pit to Top)
Cooled Surface Area		
Burner Zone		704 ft^2
Total Furnace		1951 ft^2
Volume		
Burner Zone		3520 ft^3
Total Furnace		11,544 ft^3 (to Nose)
Insulation		All Sidewalls Knuckle-up to Nose
Cooling		Spray Cooled on All Surfaces

TABLE 2-3. LWS OPERATING PARAMETERS

Parameter	Burner Firing Rate (10^6 Btu/hr) 50	75	100	Units
Heat Release Per Unit Area (Total Furnace)	28.5	39.5	56.4	10^6 Btu/hr-ft^2
Burner Zone Liberation Rate - BZLR	78.1	109.4	156.2	10^3 Btu/hr-ft^2
Heat Release Per Unit Volume (Total Furnace)	4.3	6.5	8.6	10^3 Btu/hr-ft^3
Residence Time (Total Furnace)	12.8	9.1	6.4	Sec
Residence Time (Burner Zone)	6.18	4.41	3.09	Sec
Furnace Exit Temperature	1420	1600	1900	^{o}F

furnace locations might be expected to affect the quench rate and the location of the 2250 °F isotherm. This modeling effort showed that extending the insulation up to the nose (approximately 450 ft^2 of extra insulation) would increase temperatures in the upper furnace region, and would locate the 2250 °F isotherm just under the nose when the furnace was fired at 100 x 10^6 Btu/hr. This is the position desired in order to match the expected location of this isotherm in a full-scale boiler. Thus, for the testing reported here, the LWS was fitted with additional insulation extending up to the nose. The thermal environment and temperature quench rates achieved during the tests is discussed further in Section 3.2.1.

Combustion air supplied by a forced-draft blower passes through a tubular heat exchanger and into a manifold. In the heat exchanger, the LWS combustion air is preheated by hot exhaust gas from a separate natural gas/oil-fired combustion chamber. The use of a separate combustor to preheat the air, rather than using flue gas from the LWS, allows the combustion air preheat temperature to be controlled independently of the performance of the burner firing in the LWS. The combustion air flow rate to the LWS is measured and controlled by multiple venturis and dampers. For burners equipped with a common windbox, several venturis allow accurate flow rate measurement over a wide flow rate range. In preparation for firing, the raw coal is crushed in a hammer mill followed by pulverization in a Raymond bowl mill. Coal flow rate is measured by a weigh-feeder. Primary air is taken from the main combustion air flow, with addition of tempering air or duct heater for temperature control. Air flow rate is measured by venturi flowmeter.

The furnace exhaust system is designed to permit a wide range of emission measurements. The main exhaust sampling location is near the end of a long straight duct, meeting EPA specifications for sampling point location and design. Multiple sample points are available at this location, permitting simultaneous sampling for gaseous species, SO_2 and particulate. The temperature at the sampling point is about 1000 °F. The exhaust duct is externally spray-cooled like the furnace. Downstream of the sampling location, the exhaust gas passes into a wet scrubber which controls particulate and SO_x emissions.

The LWS is equipped with a full complement of instrumentation to fully assess operating conditions, performance of the test burner, flue gas compositions, and ash characteristics. Table 2-4 lists the parameters measured, measurement methods, and data recording methods.

The outputs of all continuous instrumentation (including flow rates, temperatures, and emissions) are converted to electrical signals, put into digital notation, and supplied to a Hewlett Packard computer. The computer processes these data and provides a real-time indication of input and output parameters in engineering units. Flow rates are indicated in scfm; stoichiometries and velocities in each burner passage are calculated; and emissions are corrected to standard conditions (0 to 3 percent excess O_2).

2.2.2 Sorbent Injection Systems

The sorbent injection system, as shown in Figure 2-6, consists of a feeder, hopper and air injection system. The feeder is a commercial weigh-belt feeder similar to the one used to feed coal onto the mill. The air injection system includes an air compressor, a venturi flowmeter to monitor carrier air flow, and an ejector. The dry, powdered sorbent passes from the feeder hopper through the weigh feeder and into the ejector. The feeder's totalizer provides the actual sorbent mass flow rate, regulated by the feeder controller according to the pre-set value of mass flow.

TABLE 2-4. LWS INSTRUMENTATION AND MEASUREMENTS

Inputs			Outputs		
Parameter	**Method**	**Record**	**Parameter**	**Method**	**Record**
Burner settings	Manual	Manual	Flame characteristics	Manual and color video	Manual
Air flow rates	Calibrated Venturis	Computer	Combustion products		
Temperatures	Thermocouple	Computer	O_2	Taylor, Paramagnetic	
			CO	Anarad, NDIR	
Coal flow rates	Weigh-belt feeder and back calculate		CO_2	Anarad, NDIR	
			NO_x	TECO Chemiluminescent	Computer and Strip Chart
Coal fineness	ASME Sieve method	Manual	SO_2	Dupont, Ultra-violet	
Coal composition	Ultimate	Manual	HC	Beckman, FID	
Stoichiometry	Calculate	Computer	Particulate		
			Mass	EPA Method 5	Manual
Ambient Humidity	Hygrometer	Manual	Size distribution	Andersen, Cascade Impactor	Manual
			Composition	Ultimate Analysis	Manual
			Burner pressures	Magnahelic	Manual

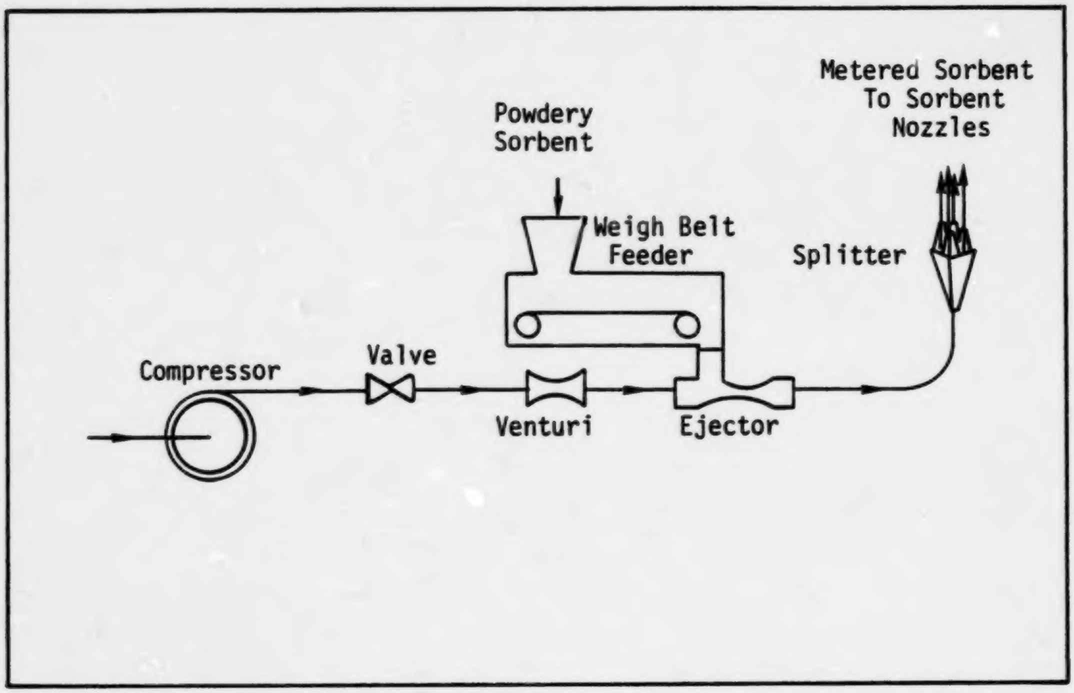

Metered Sorbent
To Sorbent
Nozzles
Powdery
Sorbent
Weigh Belt
Feeder
Splitter
Compressor
Valve
Venturi
Ejector

Figure 2-6. Diagram of LWS sorbent feed system.

As an additional measure to verify independently the actual mass flow, direct feed rate was determined by sorbent weight loss in the hopper over time during each injection test.

The metered sorbent is entrained by the carrier air in the ejector and carried to a flow splitter located close to the LWS, where the sorbent flow is divided into separate streams for delivery to the individual sorbent injectors. The splitter can divide the flow into a maximum of four separate streams. The pipes connecting the flow splitter with the sorbent injectors were made of equal length to ensure that the split was as even as possible.

Figure 2-7 depicts the specific sorbent injection locations utilized in this program. These locations included four different elevations on the furnace front wall, and one location on the furnace back wall. Table 2-5 gives the details of these specific injection locations and the type of injectors used. Single jet nozzles (usually 1 inch, sometimes 2.5 inches, in diameter) were used for all locations with the exception of Level III. At this level, where the OFA ports are located, the sorbent could be injected into the furnace in three different configurations, namely,

- as single 1-inch jet without OFA (with the 1-inch sorbent jet located axially in the center of the unused OFA port);
- mixed with OFA (i.e., as a single 6-inch jet, since the OFA ports are 6 inches in diameter)
- as double concentric jet co-axially with the OFA (i.e., as a 1-inch sorbent jet surrounded by the a 6-inch OFA jet).

The LWS was operated with overfire air only when the last two Level III injection options listed above were being used.

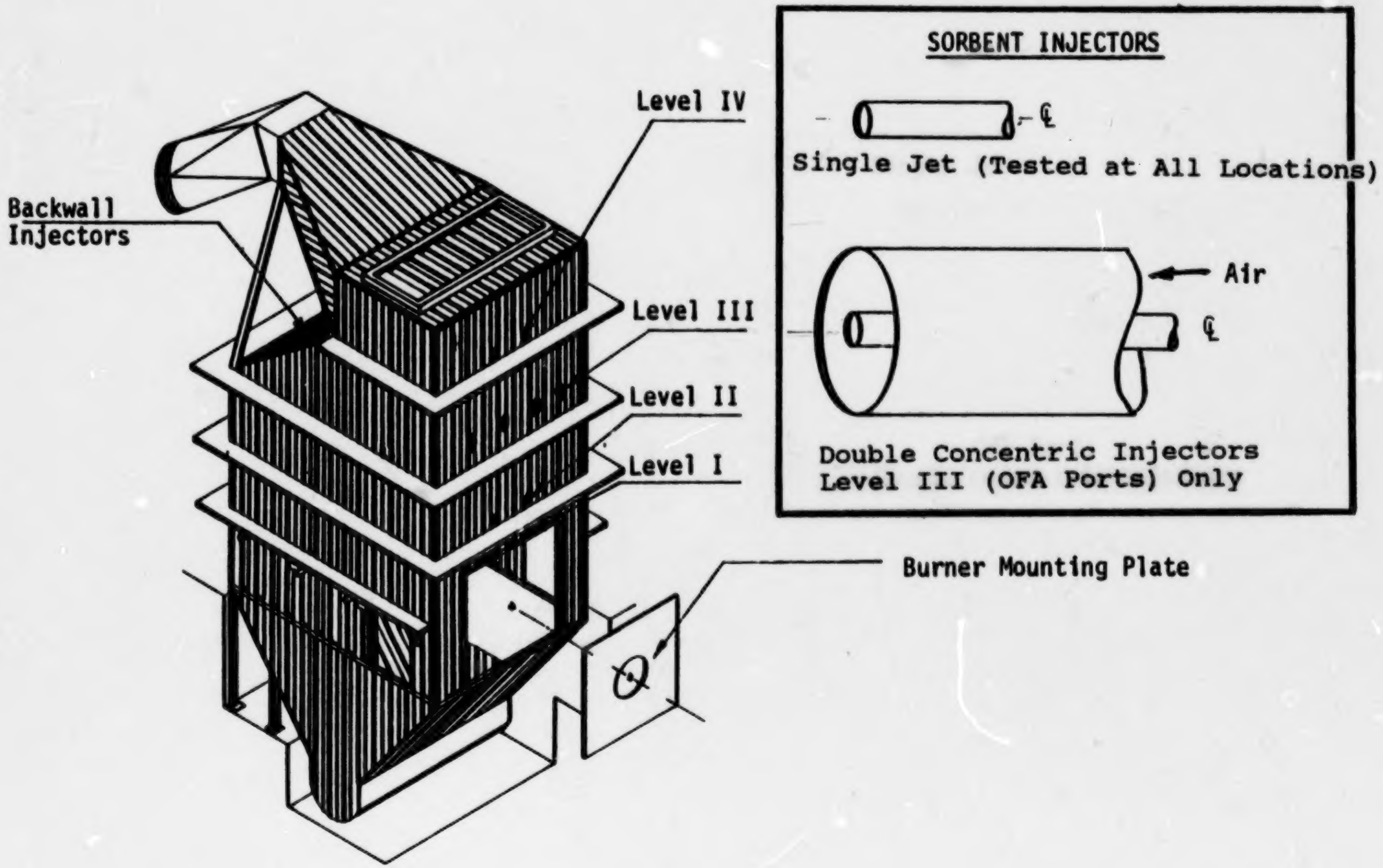

Level IV
Backwall
Injectors
Level III
Level II
Level I
SORBENT INJECTORS
℄
Single Jet (Tested at All Locations)
Air
℄
Double Concentric Injectors
Level III (OFA Ports) Only
Burner Mounting Plate

Figure 2-7. Sorbent injection location tested in the LWS furnace.

TABLE 2-5. INJECTION LOCATIONS AND INJECTOR TYPES TESTED IN LWS FURNACE

Injector Location	Distance Above Burner Centerline (ft)	Type of Injector	No. of Injectors per Location	Injector Nominal Diameter (in.)
Front wall locations				
Level I	8.0	Single-pipe jet	2	2.5
Level II	9.5	Single-pipe jet	2	1 and 2.5
Level III	19.0	Single-pipe jet	4	1 and 6
		Double concentric jet	4	1" sorbent jet inside 6" air jet
Level IV	23.8	Single-pipe jet	2	1
Back wall location				
Back wall	19.0	Single-pipe jet	4	1

2.2.3 Analytical Methods

The sampling train utilized for the continuous emission monitoring of the flue gas in the LWS facility is shown in Figure 2-8. All materials in contact with the sample are glass, 316 stainless steel, or Teflon. These materials are non-reactive with NO_x at low temperatures. The stainless steel sampling probes are water cooled, and small cyclones adjacent to the probe remove particulate matter and condensed water. The sample is then transported to the control room through a Teflon line where it is filtered and dried. The sample pump is Teflon-lined, and the sample flow rate is maintained at several times the instruments' requirements in order to minimize response time. Excess sample flow is bypassed to a vent. Commercial gas analyzers are used for measurements of O_2, CO_2, CO, NO/NO_x, and SO_2, as listed in Table 2-6. The accuracy of each instrument is maintained by frequent calibration with zero gas and certified calibration gas.

Because of the inherent problems in measuring SO_2 concentrations in a stream with reactive sorbent particles, a separate sampling system was used during sorbent injection tests. This separate SO_2 sampling system is shown in Figure 2-9. A phase discrimination probe is used, which is designed to separate particulate matter from the sample gas that passes through the SO_2 analyzer. This separation prevents the reaction of SO_2 with sorbent particles in the sampling system, a problem which can occur in conventional filter probes when reactive sorbent is present. The sample passes through a heated sample line, into a heated filter, and into a commercial permeation tube dryer installed upstream of the instrument. The SO_2 measurement is therefore determined on a dry basis. The remaining central stream of the gas sample passes through a condenser and delivers a sample for the remaining instruments.

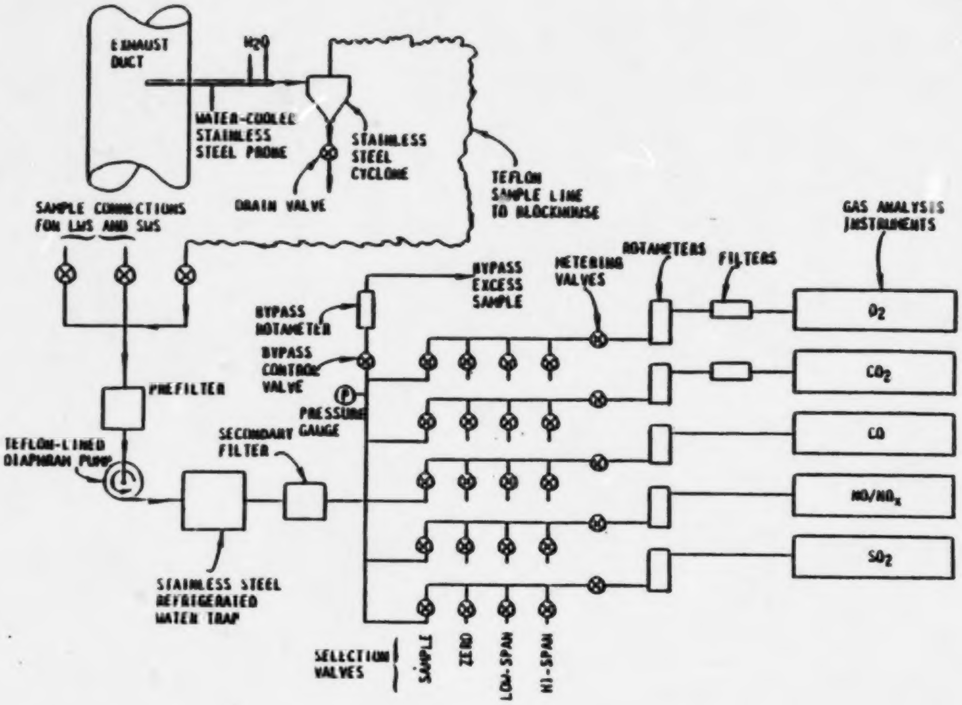
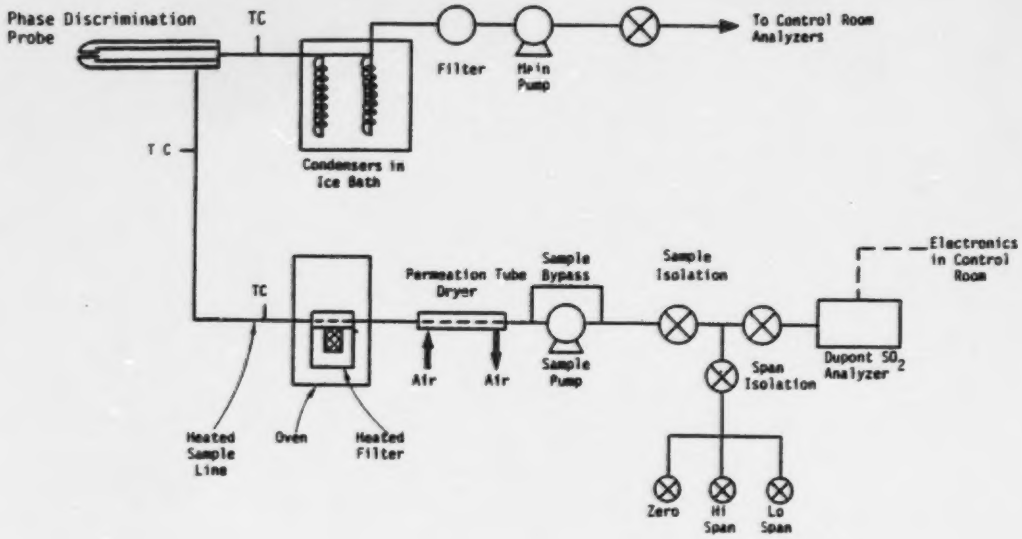

EXHAUST DUCT
H_2O
WATER-COOLED STAINLESS STEEL PROBE
STAINLESS STEEL CYCLONE
DRAIN VALVE
TEFLON SAMPLE LINE TO BLOCKHOUSE
SAMPLE CONNECTIONS FOR LWS AND SWS
GAS ANALYSIS INSTRUMENTS
ROTAMETERS
FILTERS
METERING VALVES
BYPASS EXCESS SAMPLE
BYPASS ROTAMETER
BYPASS CONTROL VALVE
P
PRESSURE GAUGE
PREFILTER
SECONDARY FILTER
TEFLON-LINED DIAPHRAM PUMP
STAINLESS STEEL REFRIGERATED WATER TRAP
O_2
CO_2
CO
NO/NO_x
SO_2
SELECTION VALVES
SAMPLE
ZERO
LOW-SPAN
HI-SPAN

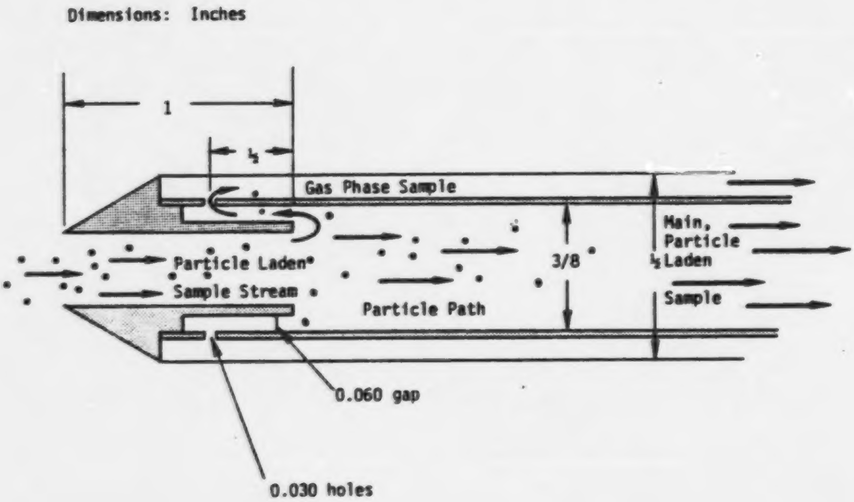
Figure 2-8. Flue gas sample train schematic.

TABLE 2-6. GAS PHASE SPECIES INSTRUMENTATION

SPECIES	OPERATING PRINCIPLE	INSTRUMENT	MODEL NO.
O_2	Paramagnetic	Beckman	755
CO_2	Nondispersive Infrared	Anarad	AR-600
CO	Nondispersive Infrared	Anarad	AR-500R
NO/NO_x	Chemiluminescence	Teco	10R
SO_2	UV Absorption	DuPont	400


Phase Discrimination Probe
TC
Filter
Main Pump
To Control Room Analyzers
TC
Condensers in Ice Bath
TC
Permeation Tube Dryer
Sample Bypass
Sample Isolation
Electronics in Control Room
Air
Air
Sample Pump
Span Isolation
Dupont SO_2 Analyzer
Heated Sample Line
Oven
Heated Filter
Zero
Hi Span
Lo Span

a) Sampling System


Dimensions: Inches
1
½
Gas Phase Sample
Main, Particle ½ Laden
Sample
3/8
Particle Laden Sample Stream
Particle Path
0.060 gap
0.030 holes

b) Phase Discrimination Probe

Figure 2-9. Schematic for sampling system for SO_2 concentration during sorbent injection tests.

The electrical signals from the gas analyzers, venturis (through pressure transducers) and thermocouples are interfaced with a computerized on-line data acquisition system, and data are printed out in convenient engineering units. Those parameters which must be recorded manually (i.e., sorbent mass flow rate, windbox pressure, etc.) are entered into the microcomputer separately through the keyboard so that the computer generated data record is a complete listing of all parameters. These computer listed raw data are included as Appendix B.

Signals from the continuous emission monitors are logged directly onto a strip chart recorder.

In addition to continuous emissions monitoring, the following samplings were performed for selected test conditions:

- EPA Method 6 (SO_2 Sample)
- EPA Method 7 (NO_x Sample)
- Pulverized coal samples (ASTM D197)
- Sorbent samples (grab)

2.3 Fuel and Sorbents

Utah coal was the sole fuel used for this phase of the program. The Utah coal, from the Star Point 1 and 2 mines in Wattis, Utah, has been used at Energy and Environmental Research Corp. (EER) as the base fuel for most of the low-emissions, high-efficiency burner development tests. It is ranked as a high volatile B bituminous coal, and is low in sulfur content and relatively high in volatile matter. A typical analysis is presented in Table 2-7. Table 2-8 lists the corresponding ASTM coal ash characteristics. Typical particle size distribution of the coal as fired is illustrated in Figure 2-10, showing acceptable fineness (approximately 73% through 200 mesh).

TABLE 2-7. TYPICAL UTAH COAL COMPOSITIONS

Reporting Basis	As Received	Dry
Proximate (wt %)		
Moisture	6.63	0.00
Volatile	42.12	45.11
Fixed Carbon	45.08	48.28
Ash	6.17	6.61
Ultimate (wt %)		
Moisture	6.63	0.00
Carbon	69.92	74.88
Hydrogen	5.22	5.59
Nitrogen	1.32	1.41
Sulfur	0.59	0.63
Ash	6.17	6.61
Oxygen*	10.15	10.88
Heating Value		
Btu/lb	12,554	13,445
MMF Btu/lb		14,499
MAF Btu/lb		14,396
Forms of Sulfur (As S, %)		
Sulfate	0.01	0.01
Pyritic	0.06	0.06
Organic	0.52	0.56

* Oxygen by Difference

TABLE 2-8. TYPICAL UTAH COAL ASH CHARACTERISTICS (ASTM)

Elemental Ash (%)	
SiO_2	58.42
Al_2O_3	18.45
TiO_2	0.87
Fe_2O_3	4.49
CaO	6.88
MgO	0.95
Na_2O	2.13
K_2O	0.83
P_2O_5	0.40
SO_3	5.52
Ash Fusion Temperature (^oF)	
Oxidizing Atmosphere	
Initial deformation temp	2323
Softening temperature	2425
Hardening temperature	2465
Fluid temperature	2554
Reducing Atmosphere	
Initial deformation temp	2220
Softening temperature	2375
Hardening temperature	2476
Fluid temperature	2528
Ash Type	Lignite

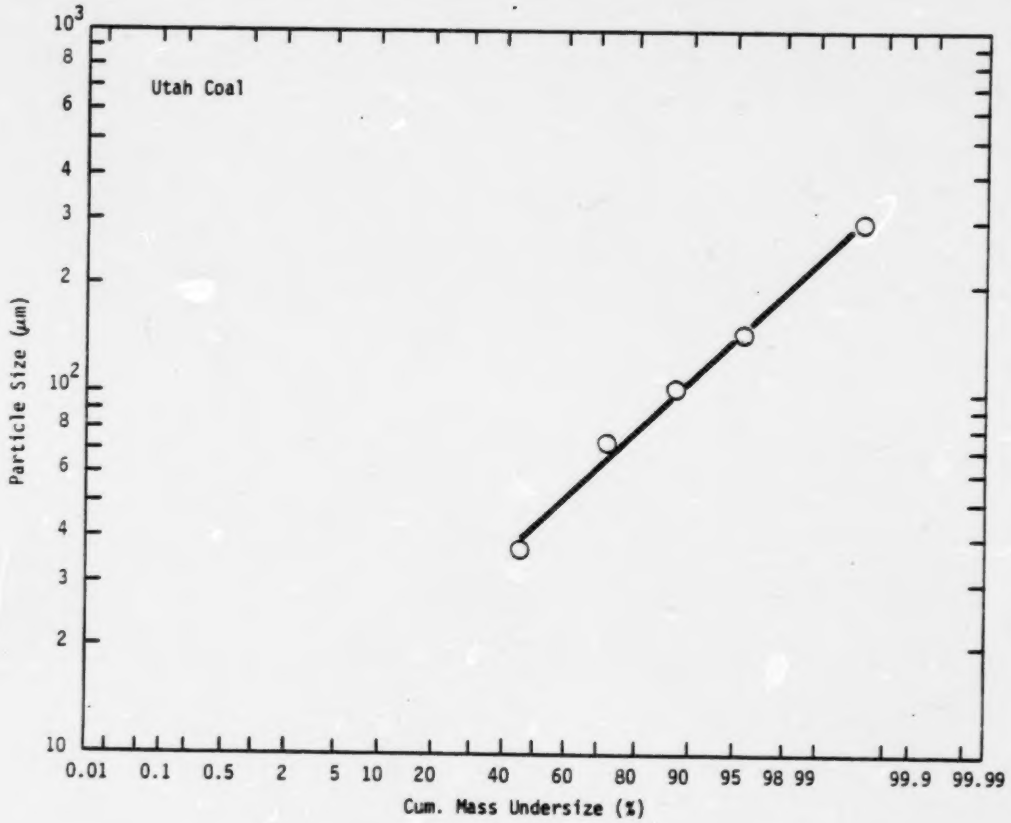


Figure 2-10. Test fuel particle size distribution.

The sorbents tested in this program were a calcitic limestone, a dolomite, and a pressure-hydrated dolomitic lime, representing markedly different physical and chemical properties. Some of the characteristics of these three sorbents are compared in Table 2-9. The limestone, Vicron 45-3, is a natural calcite containing 56 percent CaO, and has been pulverized to a mass mean particle size of about 10 microns; this is the sorbent that was used for most of the tests reported here. The Vicron served as a baseline sorbent to compare the sulfur capture performance of the other sorbents. Limited tests were conducted with dolomite D3002 (a pulverized calcium magnesium carbonate), and with Genstar Type-S pressure-hydrated dolomitic lime (PHDL). The dolomite used was about 35 percent CaO and 19 percent MgO, and had a mass median diameter of approximately 12 microns. Type-S lime is characterized by its small particle size (mass median diameter of about an order of magnitude smaller than that of dolomite) and relatively high MgO content (about 27%). Typical size distributions obtained with full size analysis for these three sorbents are shown in Figure 2-11.

2.4 Test Procedures

Established standard procedures were applied during the tests in accordance with the guidelines set by the Quality Assurance Project Plan (QAPP). Specific quality assurance activities are detailed in Appendix A. Standard measurement format was used for all tests unless indicated otherwise. The key input and output parameters measured during these tests are listed in Table 2-10.

TABLE 2-9. TYPICAL SORBENT PROPERTIES

Sorbent	Type	CaO (%)	MgO (%)	True Density (g/cc)	Median Diameter (ESD μm)
Vicron 45-3	$CaCO_3$	55.64	0.54	2.706	9.8
Dolomite D3002	$CaMg(CO_3)_2$	34.67	18.79	2.871	12.0
PHDL, Type-S	$CaMg(OH)_4$	42.48	26.67	2.289	1.4

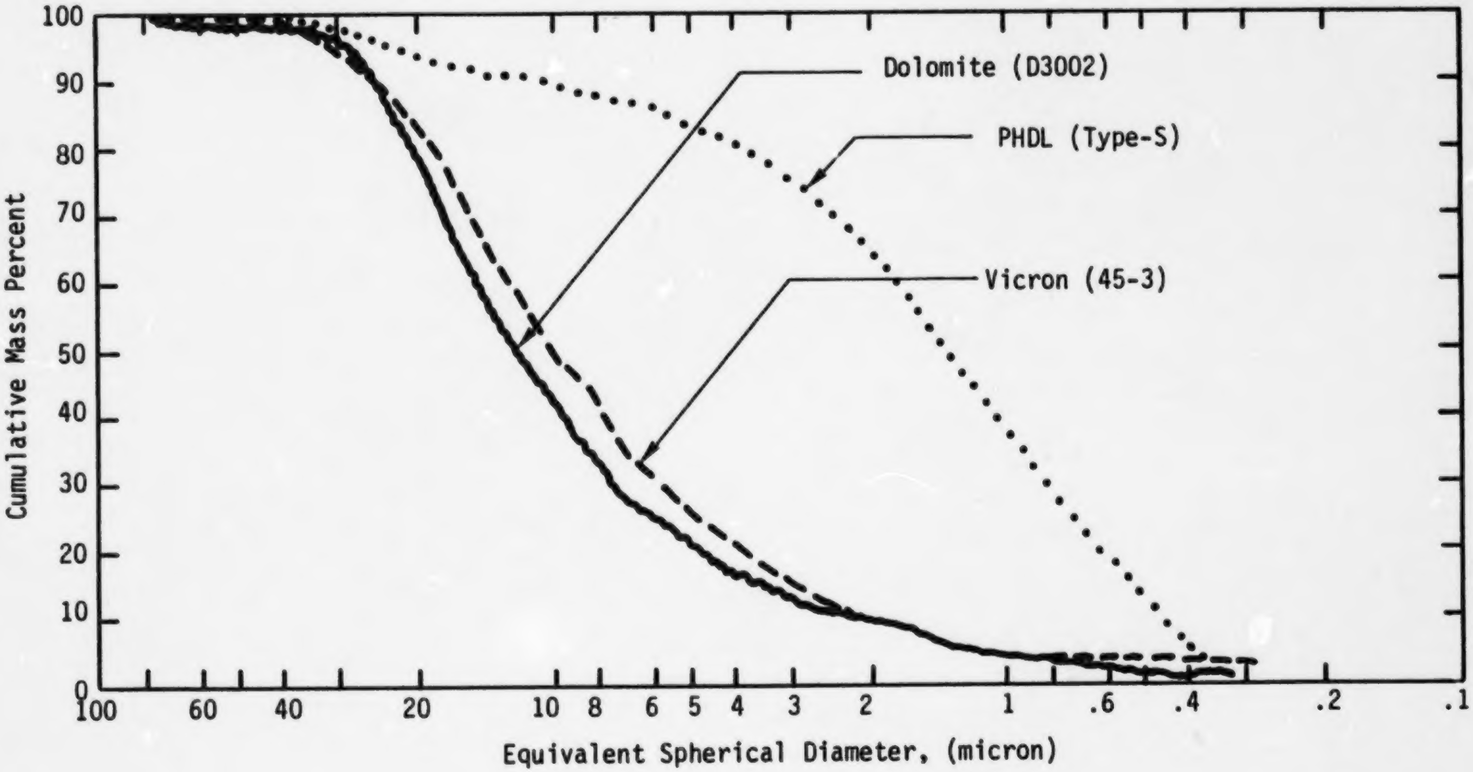


Figure 2-11. Sorbent particle size distributions.

TABLE 2-10. STANDARD MEASUREMENT FORMAT

Input Parameters	Output Parameters
Burner Setting	Flame Characteristics
Combustion Air Flow Rate	Combustion Products: (Gas Phase)
Combustion Air Flow Temp.	- O_2
	- CO
Fuel Flowrate	- CO_2
	- NO_x
Sorbent Injection Location	- SO_2
Sorbent Flow Rate	Burner/Furnace Pressures
Sorbent Carrier Air Flow	Flue Exit Temperatures

3.0 EXPERIMENTAL RESULTS

This section of the report describes the results of the experiments conducted in the Large Watertube Boiler Simulator (LWS) with the unstaged and staged (annular and axial) versions of the Internally-Staged (IS-100) burner. The tests were devoted primarily to evaluating SO_2 removal potential. Brief parametric tests were first conducted to optimize the IS-100 burners, followed by a series of screening tests to identify the effect of sorbent injection location/configuration on sulfur capture potential.

All emission results presented in this section of the report are on dry basis and are corrected to zero percent O_2. The SO_2 capture values are derived from SO_2 concentrations measured with and without sorbent injection. The capture values are therefore not based on a theoretical SO_2 yield, and take no credit for inherent SO_2 capture by the coal ash.

3.1 Burner Optimization

Table 3-1 summarizes the brief parametric study conducted to optimize the two burner designs. The primary concern of this task was to achieve NO_x and CO emissions as low as possible, and at the same time obtain relatively good flame stability and flame shape. Hence, this brief study was designed to test only a few key burner parameters (i.e., register swirl level, coal splitter position, etc.); the objective was to identify a suitable burner configuration which would meet the above objectives and provide a suitable low-NO_x burner for use in the sorbent injection portion of the testing.

The initial unstaged (annular) configuration of the burner was a typical pre-NSPS burner, equipped with a single register and a straight annular coal nozzle. Following this, an axial coal

TABLE 3-1. PARAMETRIC TEST MATRIX FOR BURNER OPTIMIZATION

Parameters	Annular Nozzle	Axial Nozzle	
		T-15	T-30
Register Setting	15° to 50°	15° to 50°	15° to 50°
Core Air	14 to 28 ft/sec.	NA	NA
Splitter Position	NA	2 to 14 in.	Fixed
Overfire Air	No	No	0-11%

NA - Not Applicable

nozzle, first with a T-15 coal splitter and then with a T-30 splitter, was installed to explore the NO_x reduction potential with these possible coal nozzle modifications aimed at achieving internal staging. In the tables that follow, the total stoichiometric ratio SR_T -- which, consistent with Table 2-1, is usually 1.2 -- is the sum of the burner zone stoichiometric ratio SR_B and the overfire air ratio (SR_{OFA}) where OFA is used. SR_B is the sum of the primary air (SR_P) -- which also includes the core air in the annular burner -- and the secondary air (SR_{Sec}).

The test results for these three coal nozzle configurations are summarized in Figures 3-1 through 3-4. The NO_x emissions were high for the annular coal nozzle configuration, as expected for a typical pre-NSPS burner. The swirl was varied; the impact of swirl (Figure 3-1) was to increase NO_x from 830 ppm to 910 ppm as the register was varied from mild swirl (register setting 50°) to high swirl (15°). As the swirl was decreased, flame stability was not compromised, and the CO emissions were found to be relatively insensitive to the change of swirl level within the range of the experiments.

For the axial coal nozzle configuration, both T-15 and T-30 coal splitters gave substantially lower NO_x emissions than the annular coal nozzle, as would be expected. NO_x emissions ranged from 550 to 775 ppm as the register setting was varied; these emissions are approximately 25% lower than those seen with the unstaged annular burner, and are similar to the performance achieved in the SWS with these coal splitters (1). The NO_x emissions for these two splitter configurations dropped sharply as the level of swirl decreased. Low swirl intensity normally generates slow mixing resulting lower NO_x emissions. The flame length produced with low swirl level also tends to be longer as observed from the experiments.

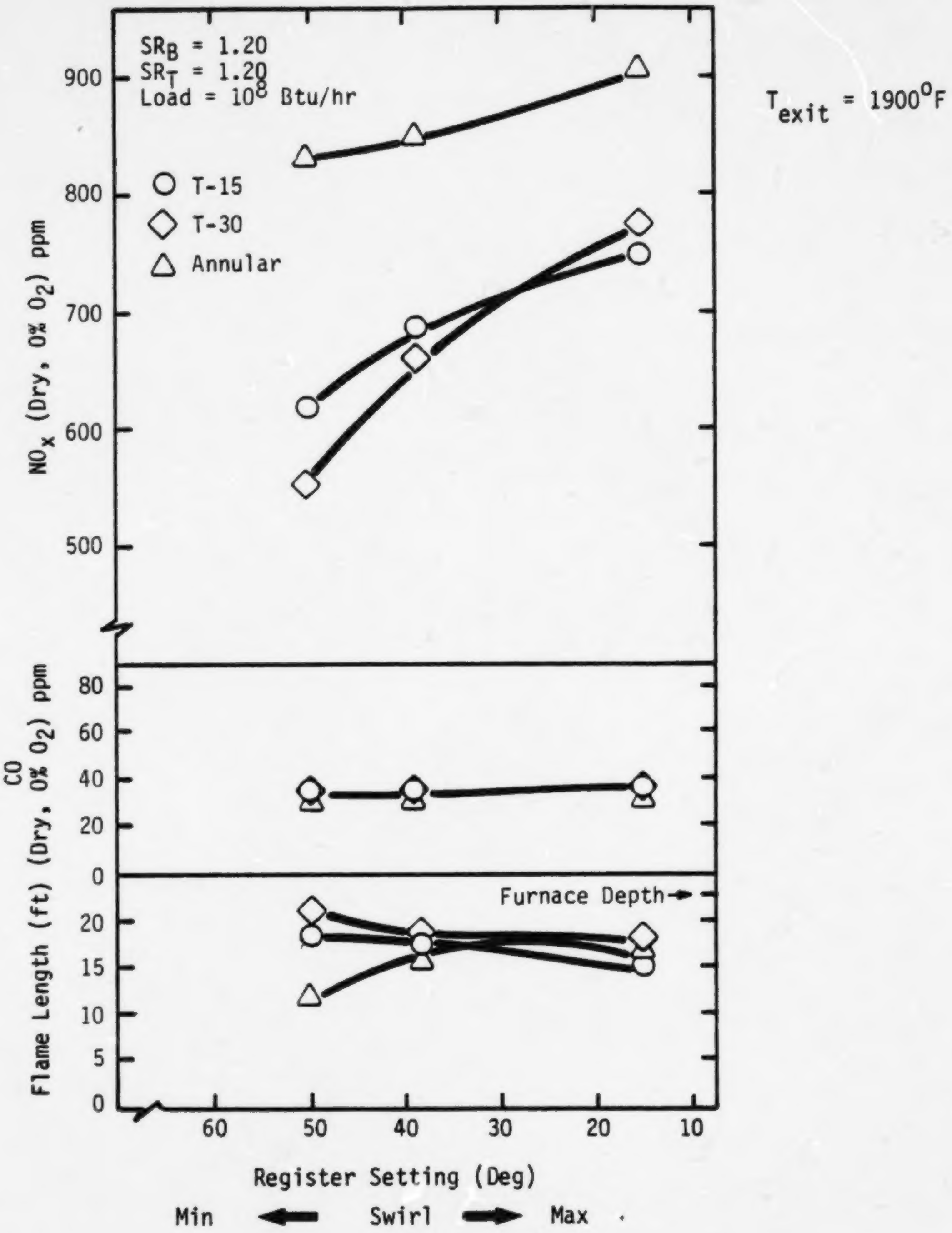


Figure 3-1. IS-100 burner optimization. Effect of register (swirl) on NO$_x$, CO emissions and flame length.

The influence of the core air on emissions and flame stability for the annular coal nozzle was also investigated. The primary function of the core air is to provide cooling to the ignition equipment. In addition, it establishes a bluff body recirculation zone at the root of the flame so that the flame stability can be improved. For this test, the burner register was set to 50 degrees, the best register position in accordance with the results observed in the previous optimization test (Figure 3-1). NO_x was about 50 ppm higher when the core air velocity was doubled (Figure 3-2). The increase of the core air velocity was achieved by doubling the core air flow rate while maintaining the primary air flow rate constant; as a result, the stoichiometric ratio in the primary zone SR_P (primary air plus core air) increased accordingly. The corresponding increase in oxygen in the primary zone could have contributed to the increase in NO_x. No noticeable flame improvement was observed when core air was increased. CO emissions were not affected.

Figure 3-3 shows the results of NO_x and CO emissions as a function of primary air velocity for the T-15 coal splitter configuration. During the test, both the swirl register setting and SR_P were kept constant. The primary air velocity was varied by changing the position of the coal splitter with respect to the exit of the coal nozzle. The data show that high primary velocity seems to favor the reduction of NO_x as well as CO emissions. The reduction of NO_x may be the result of changing the mixing process in the complex flow field near the burner quarl.

All of the testing reported above was conducted with no overfire air, i.e., with all air being introduced in the burner zone. The effect on NO_x emissions of using overfire air was tested with the axial burner equipped with the T-30 coal splitter. See Figure 3-4. Holding the total air constant at $SR_T = SR_B + SR_{OFA} = 1.21$, burner zone stoichiometry ($SR_B = SR_P + SR_{Sec}$) was varied between 1.05

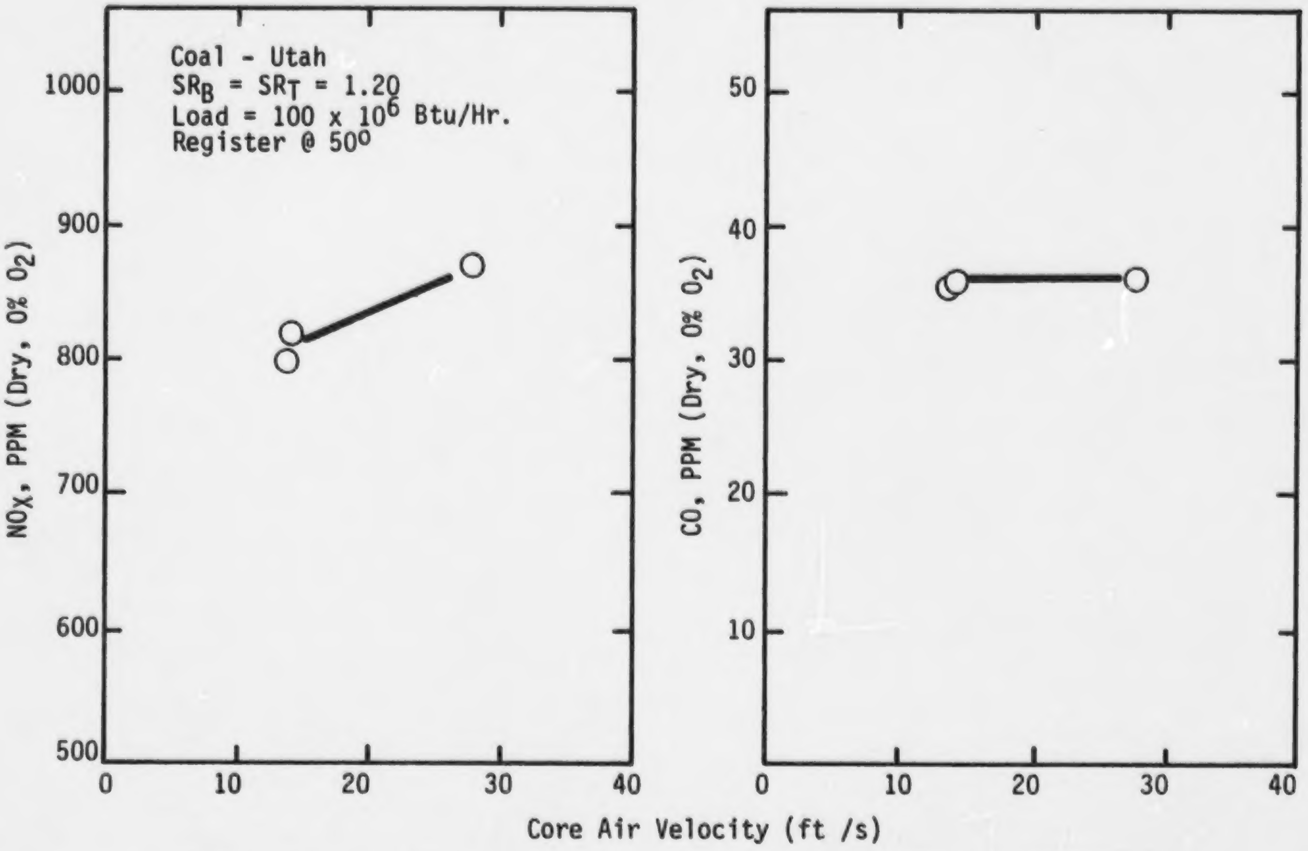


Figure 3-2. Influence of core air on NO_X and CO emissions for the annular coal nozzle burner design.

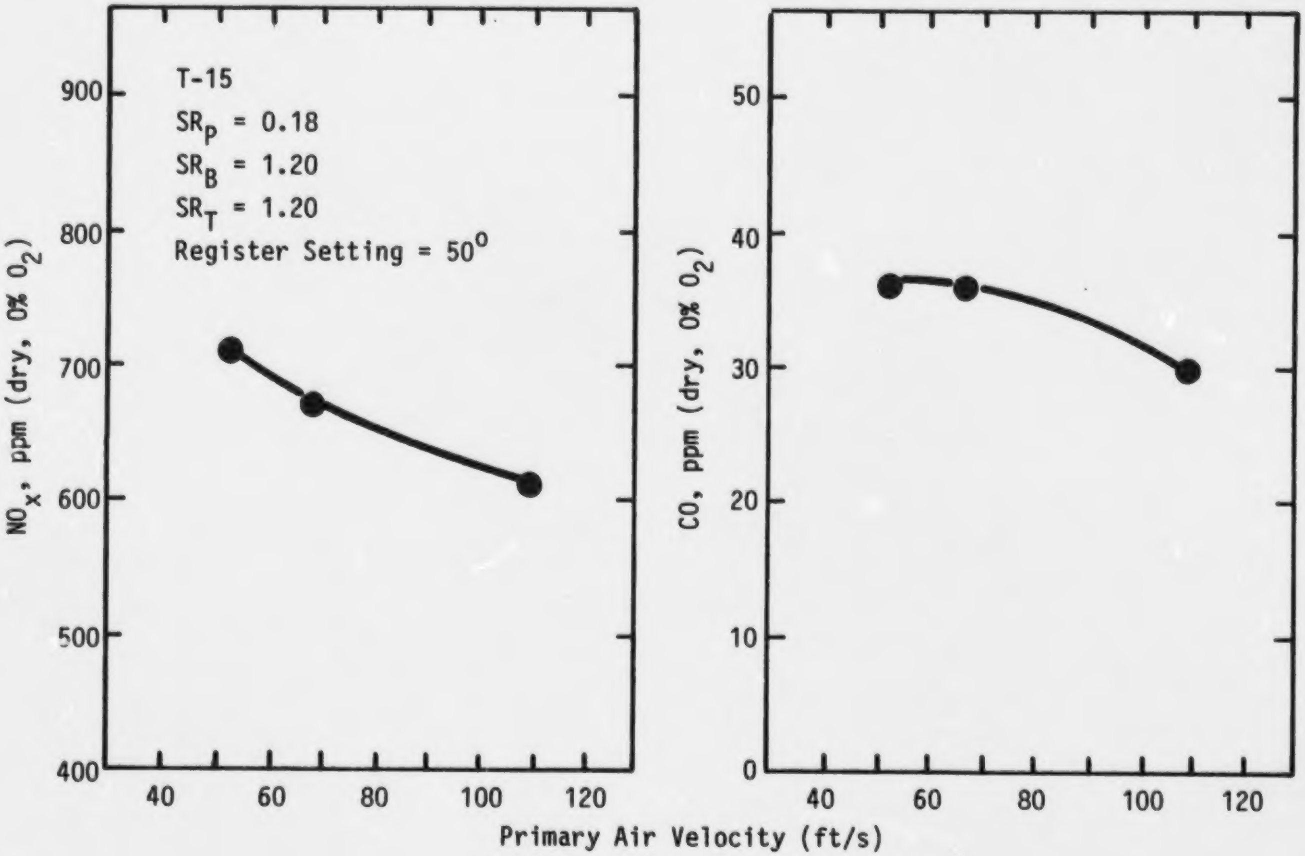


Figure 3-3. Effect of primary air velocity on NO_x and CO emissions for the axial coal nozzle with T-15 splitter design.

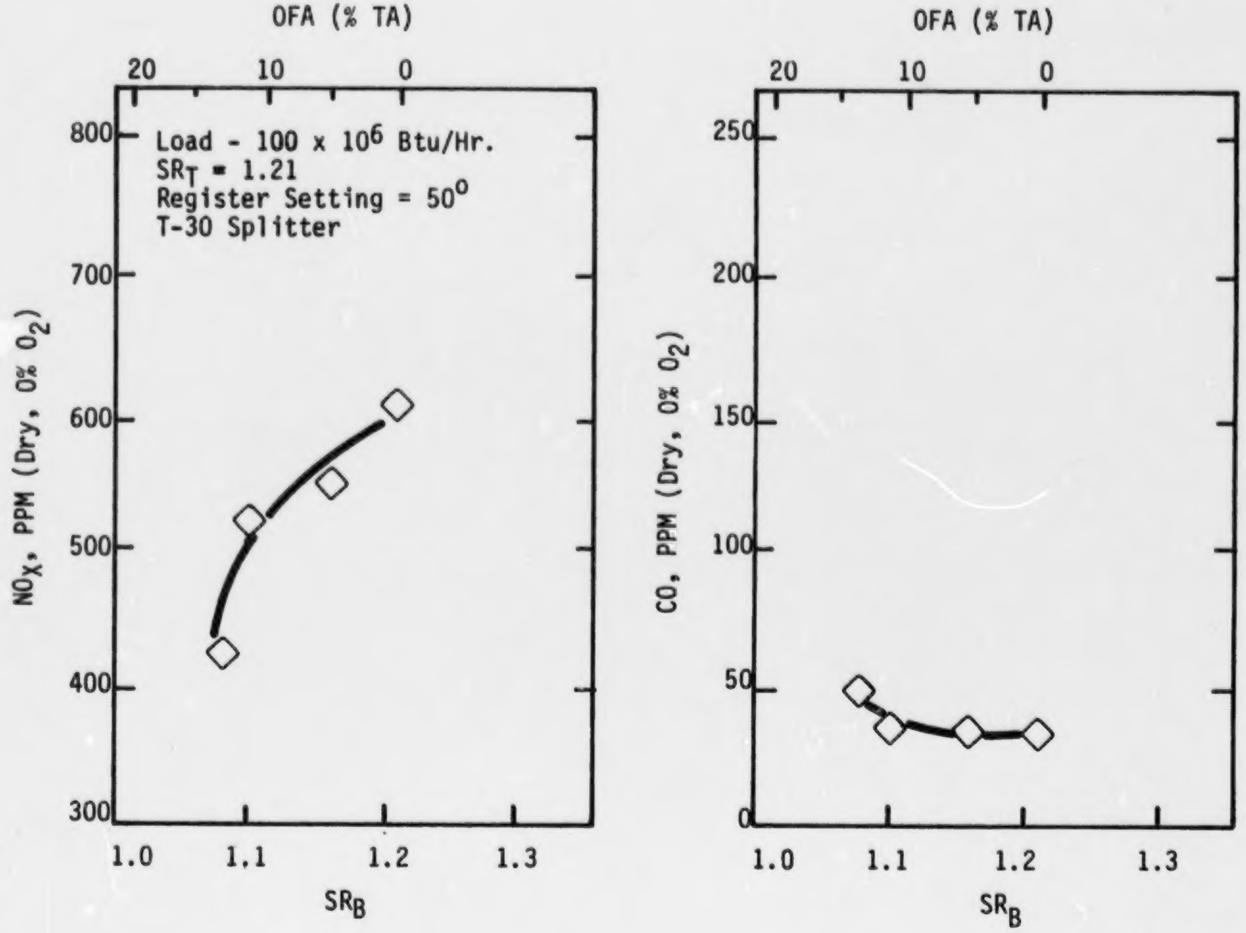


Figure 3-4. Effect of burner zone stoichiometry on NO_x and CO emissions. IS-100 axial coal nozzle with the T-30 splitter.

and 1.21, always above 1.0 (i.e., the overfire air was varied from zero to 15% of theoretical air). It can be seen that a considerable reduction of about 200 ppm (approximately 30%) can be achieved with about 13 percent theoretical air through the OFA ports. CO emissions with OFA were slightly higher than the baseline condition, but were still well within the acceptable level of 50 ppm.

Based upon the brief burner optimization testing reported above, the axial burner with the T-30 coal splitter was selected for the subsequent sorbent injection testing. Thus, all of the SO_2 testing reported below was conducted with this burner. However, the optimization process was necessarily brief, in view of the project emphasis on the sorbent injection tests; thus, the axial/ T-30 burner should be viewed only as the "most suitable" option under the circumstances, and not necessarily as a truly optimum low-NO_x burner configuration.

3.2 Sorbent Injection Studies

The tests described in this subsection of the report are aimed at providing performance information on systems of injecting calcium-based dry sorbent of small particle size to lower SO_2 emissions.

The parameters studied in this task included:

- Injector configuration parameters
- Operational parameters

The injector configuration parameters studied were: location of injectors (i.e., near the burner vs. remote from the burner zone, and position remote from the burner); the number of injectors in a bank, to evaluate the effect of sorbent dispersion; the size of the injector, to study the effect of jet size/momentum on penetration in crossflow; and the injection configuration (i.e., single-pipe jet vs. double-concentric jet).

The operational parameters studied were: sorbent types; Ca to S molar ratio; and sorbent injection velocity V_j. In testing double-concentric jets, the annular air jet velocity V_A was held constant at 65-70 ft/s. Table 3-2 summarizes all the parameters investigated in this phase of study.

3.2.1 Initial Tests

The initial trial in evaluating the injector configuration parameters involved an attempt to assess the effects on SO_2 capture of different injection locations away from the immediate burner zone. The front wall injection locations selected for this testing were chosen recognizing the effect of peak temperature on sorbent deactivation, and using an existing mathematical model for predicting boiler thermal profiles throughout the LWS furnace. Levels I and II were injection locations selected relatively near to the burner, but still away from the immediate burner zone. Injection at these locations simulates injection through the top row of burners in a full-scale bank of utility burners when that top row is operating only with air, as would be the case if the burners-out-of-service (BOOS) firing concept is being utilized. Consideration of the LWS thermal profile suggests that temperatures at Levels I and II are not dramatically above the 2250 °F upper limit of the sulfation temperature "window". To test upper-furnace injection more remote from the burner, Levels III and IV were chosen, since these locations give injection temperatures near the upper limit of the sulfation window. It would be hoped that injection at Levels III and IV would avoid sorbent overheating and yet provide sufficient residence time for the sorbent at sulfation temperatures in the furnace.

TABLE 3-2. SUMMARY OF PARAMETERS INVESTIGATED IN THE SO_2 STUDY

Injector Configuration Parameters				Operating Parameters				
Injector Location	Injector Configuration	Number of Injectors	Injector Nozzle Diameter* (in.)	Sorbent Type	Ca/S Molar Ratio	Injection Velocity V_J (ft/s)	Injection Configuration	Load 10^6 Btu/hr
Level I	Single Jet	2	2 1/2	Vicron	2-3.5	54	Discrete Jet	60
Level II	Single Jet	2	1	Vicron	1.9-2.4	162-243	Discrete Jet	100
		2	2 1/2	Vicron	1.4-3.0	56	Discrete Jet	60
		2	2 1/2	Vicron	1.5-3.0	59	Discrete Jet	100
Level III	Single Jet	4 and 2	1	Vicron	2.1-2.9	82-162	Discrete Jet	100
	Single Jet	4 and 2	6	Vicron	1.5-3.3	18-78	Mixed with OFA	100
	Dbl. Conc. Jet	4 and 2	1	Vicron	1.7-3.2	118-153	Discrete Jet w/OFA	100
	Dbl. Conc. Jet	4	1	Dolomite	1.4-3.2	81-151	Discrete Jet w/OFA	100
	Dbl. Conc. Jet	4	1	PHDL	1.6-3.5	81-151	Discrete Jet w/OFA	100
Level IV	Single Jet	2	1	Vicron	1.6-2.8	162-253	Discrete Jet	100
Backwall	Single Jet	4	1	Vicron	2-4.3	80-151	Discrete Jet	100
	Single Jet	4	1	Dolomite	1.5-2.1	118	Discrete Jet	100
	Single Jet	4	1	PHDL	1.7-3.2	118	Discrete Jet	100

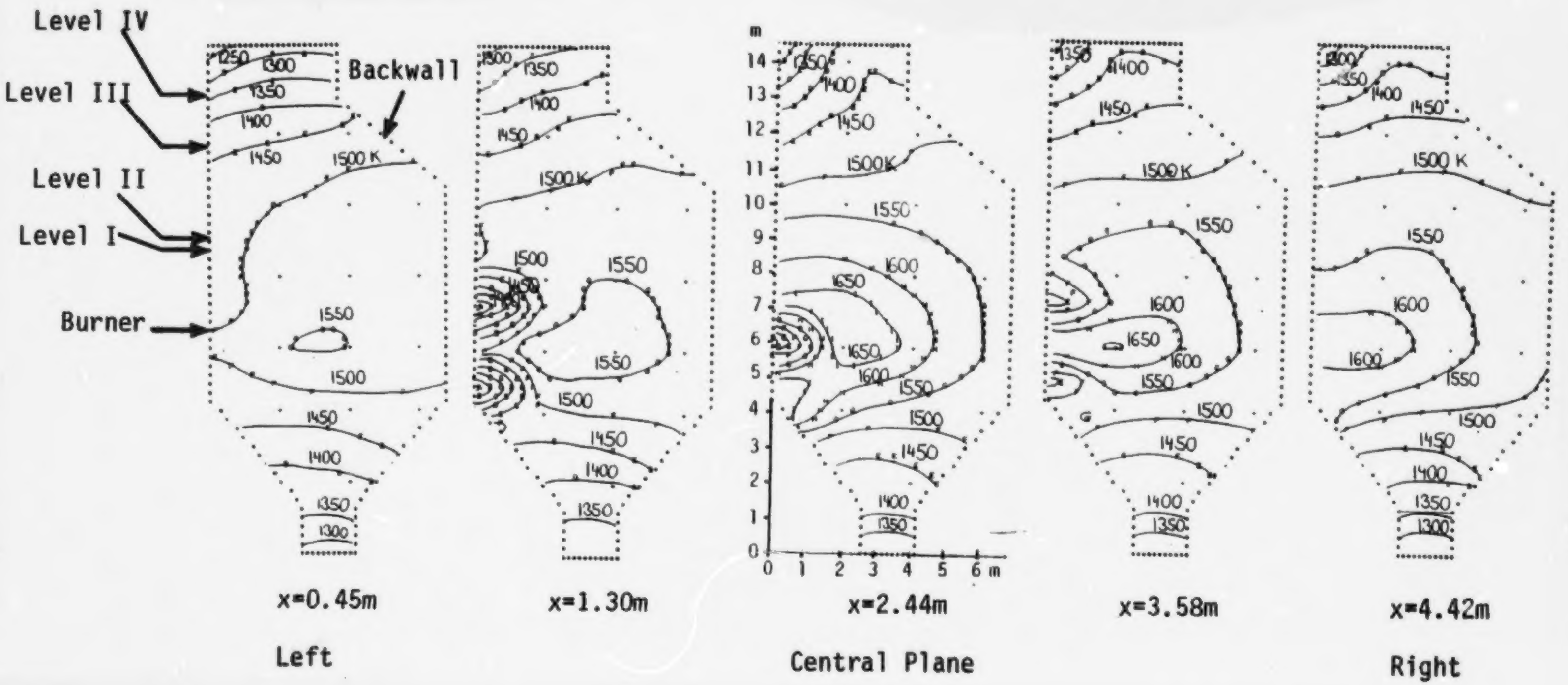
* Nominal pipe size (Schedule 40). Diameter given is that of sorbent jet; for double concentric jets, this sorbent jet is surrounded by the 6-inch annular air jet (the OFA port).

Estimates of the thermal environment in the LWS furnace were made with EER's General Boiler Thermal Analysis Code (GBTAC), which is a zone model that uses an estimate of the furnace flow pattern based on isothermal flow model results. The GBTAC estimate for the temperature field in the LWS operating at the conditions set for these tests is shown in Figure 3-5. This figure also shows the injection levels that were used. Level III was selected specifically to provide injection at a temperature of approximately 2250 °F (1500 °K), which was considered near optimum from the results of other upper furnace sorbent injection studies.

Figure 3-6 shows the predicted temperature history in the LWS, starting from the point in the furnace above the burner where the full burner mass flow has been reached. Temperature falls slowly in the upper part of the furnace, partly because the LWS had extra insulation added for these studies, and then falls more rapidly in the exhaust transition and duct. Overall the residence time in the sulfation temperature window (2250 - 1750 °F) is about 2 seconds, giving an average quench rate of 285 F°/sec. Figure 3-6 also shows measured temperatures in the LWS. The measurements agree very well with the predictions, particularly at furnace exit. The temperature measured at Level III is slightly lower than the prediction, but this was a single point measurement whereas the prediction was for the average temperature over the furnace cross-section.

The SO_2 capture results of this initial trial are compared in Figure 3-7 for injector banks placed at Levels II, III and IV. For this testing, each injector bank was equipped with two nozzles of one inch in diameter (nominal pipe size). Vicron 45-3 limestone, the baseline sorbent, was injected into the furnace at a sorbent jet velocity V_j of about 160 ft/s. The data show essentially no influence of furnace elevation along the front wall on SO_2 capture. Furthermore, the SO_2 capture at Ca/S = 2.0 (about 15%) was relatively low compared to other results obtained from previous

Assumptions: LWS operating at 100 x 10^6 Btu/hr burning Utah coal. Insulation installed up to furnace nose. 20% excess air (SR_T = 1.20).



x = distance from left wall. Bulk temperature at exit = 1405 °K (2069 °F).

Figure 3-5. Prediction of the thermal profiles for the LWS furnace using the GBTAC mathematical model.

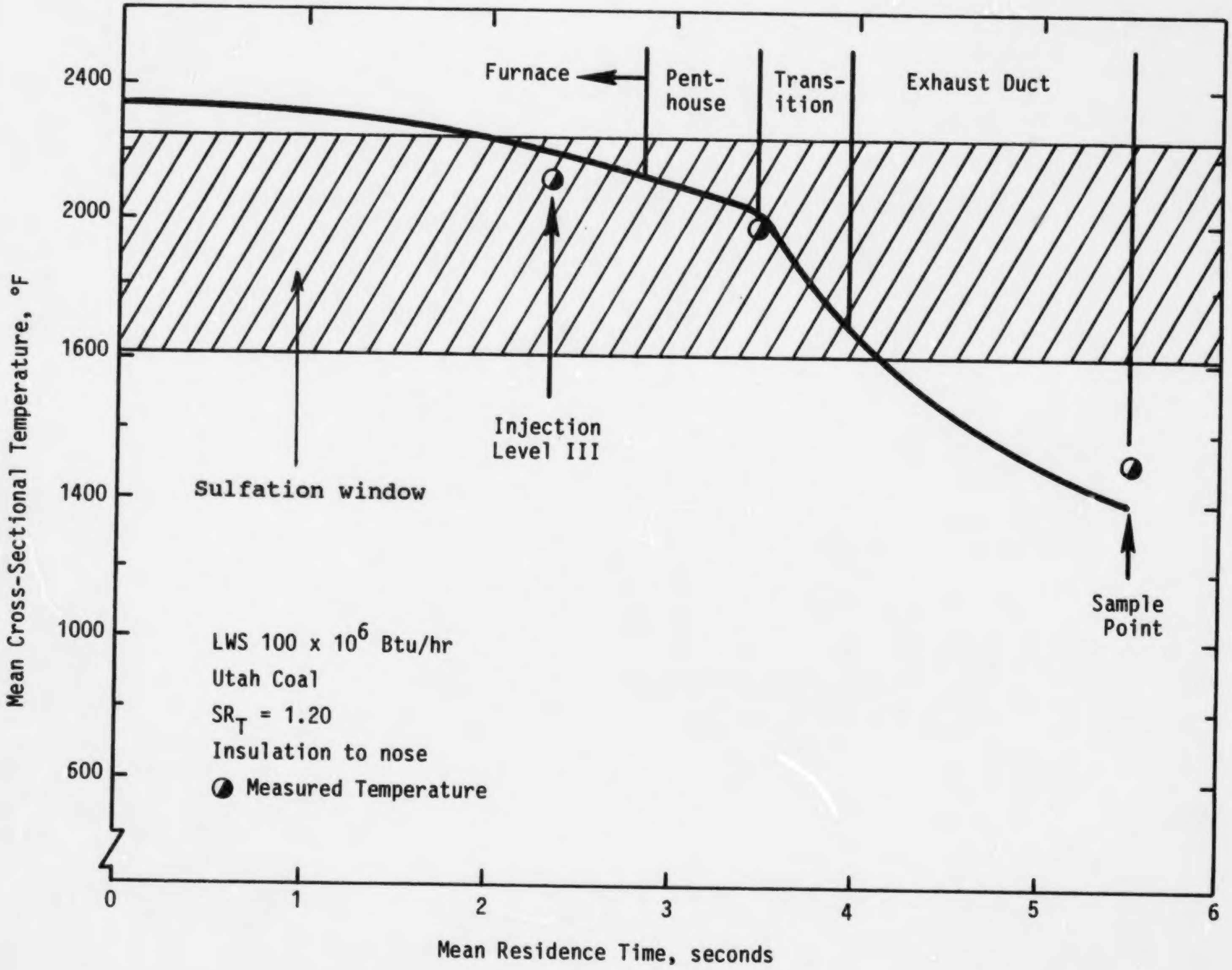


Figure 3-6. Predicted temperature history in LWS.

burner tests in the LWS. This was an unexpected result, because the injection locations and the predicted temperature histories indicated that SO_2 capture would be good, at least for injection from Levels III and IV. It was suspected that the low SO_2 capture might have been a result of dead-burning of the injected sorbent, even though injection in the upper furnace had been intended to avoid such a problem.

In order to assess the possibility that dead-burning was occurring, a test was conducted where the sorbent was pre-mixed with the pulverized coal. Presumably, this test should reflect the worst possible dead-burning effects. The result of the coal/ sorbent pre-mixing test is shown in Figure 3-7 along with the wall injection results. As can be seen, the pre-mixing results are no poorer than the results obtained with wall injection at any of the Levels.

As a further test of dead-burning effects, another near-burner injection configuration (Figure 3-8) was tested. The objective was to either further confirm the effects of near-burner sorbent deactivation, or to determine whether such dead-burning could be avoided by careful design of the near-burner sorbent injectors. This injection configuration consisted of installing 4 injectors of 1 inch in diameter evenly spaced about the coal nozzle within the secondary air channel, parallel to the flow. The end of each injector was bent at an angle of 25° (the same angle as the quarl), such that the exit of the sorbent jet was parallel to the divergent section of the burner. Furthermore, the injectors could be rotated 360°, so that sorbent could be injected either away from the flame (parallel to the quarl) or toward the flame. Test results for this special injection configuration are compared in Figure 3-9 with the results obtained when the coal and the sorbent were premixed and fed together. The special secondary-air-channel in-burner injection configuration yielded slightly higher sorbent utilizations

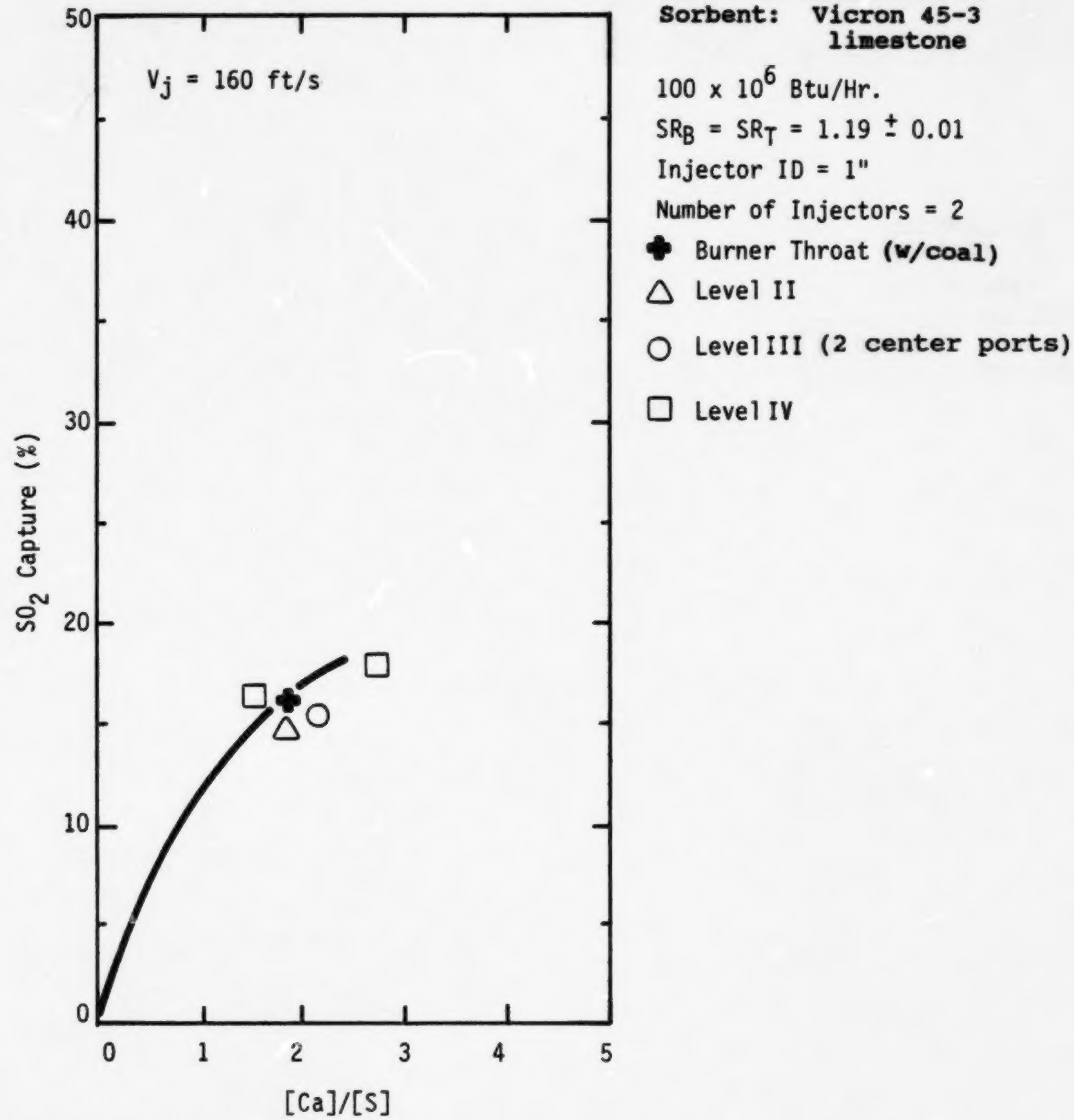


Figure 3-7. Influence of different front wall elevations on sulfur capture potential.

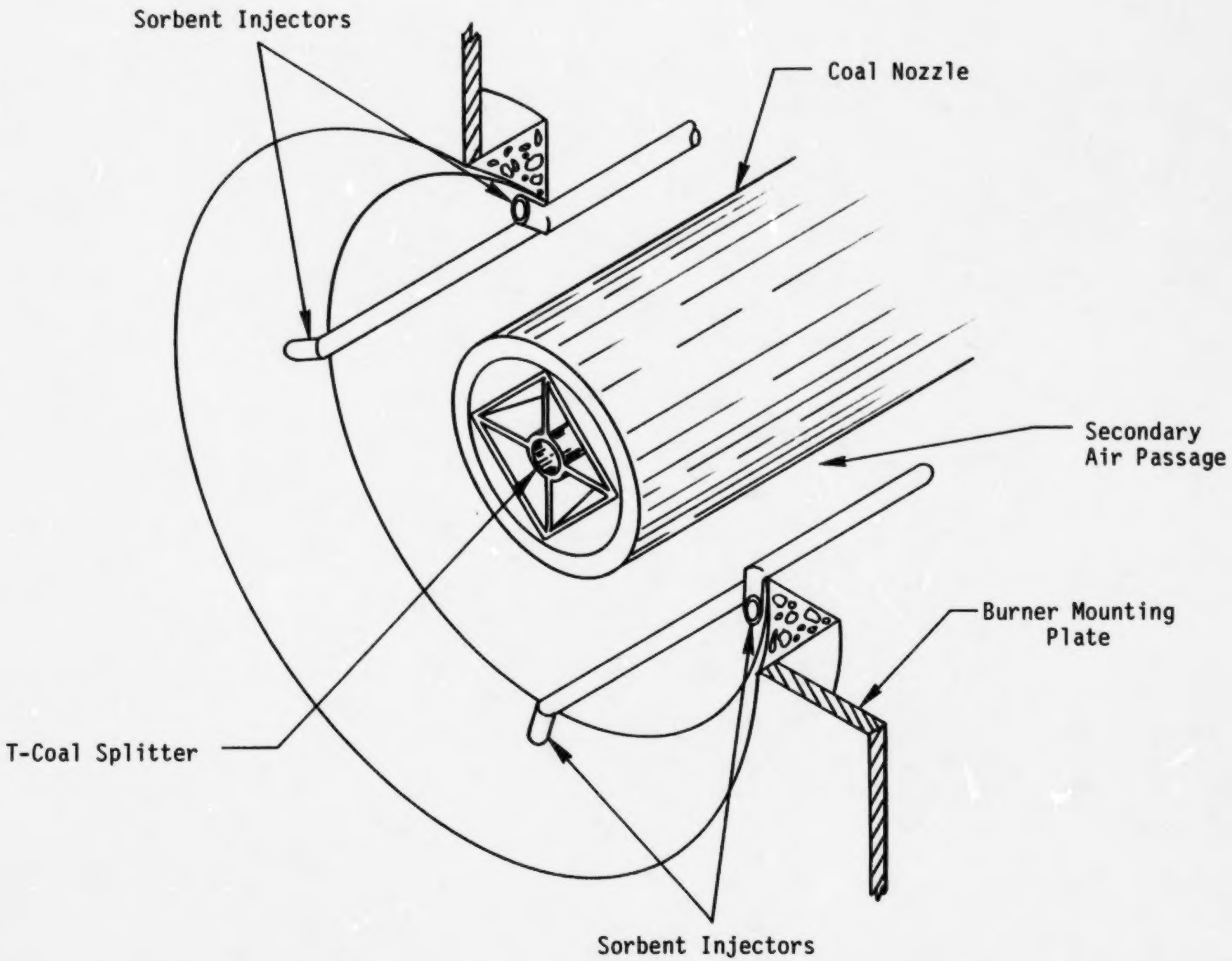

Sorbent Injectors
Coal Nozzle
Secondary Air Passage
Burner Mounting Plate
T-Coal Splitter
Sorbent Injectors

Figure 3-8. Configuration of four sorbent injection tubes in the secondary air channel of the IS-100 burner.

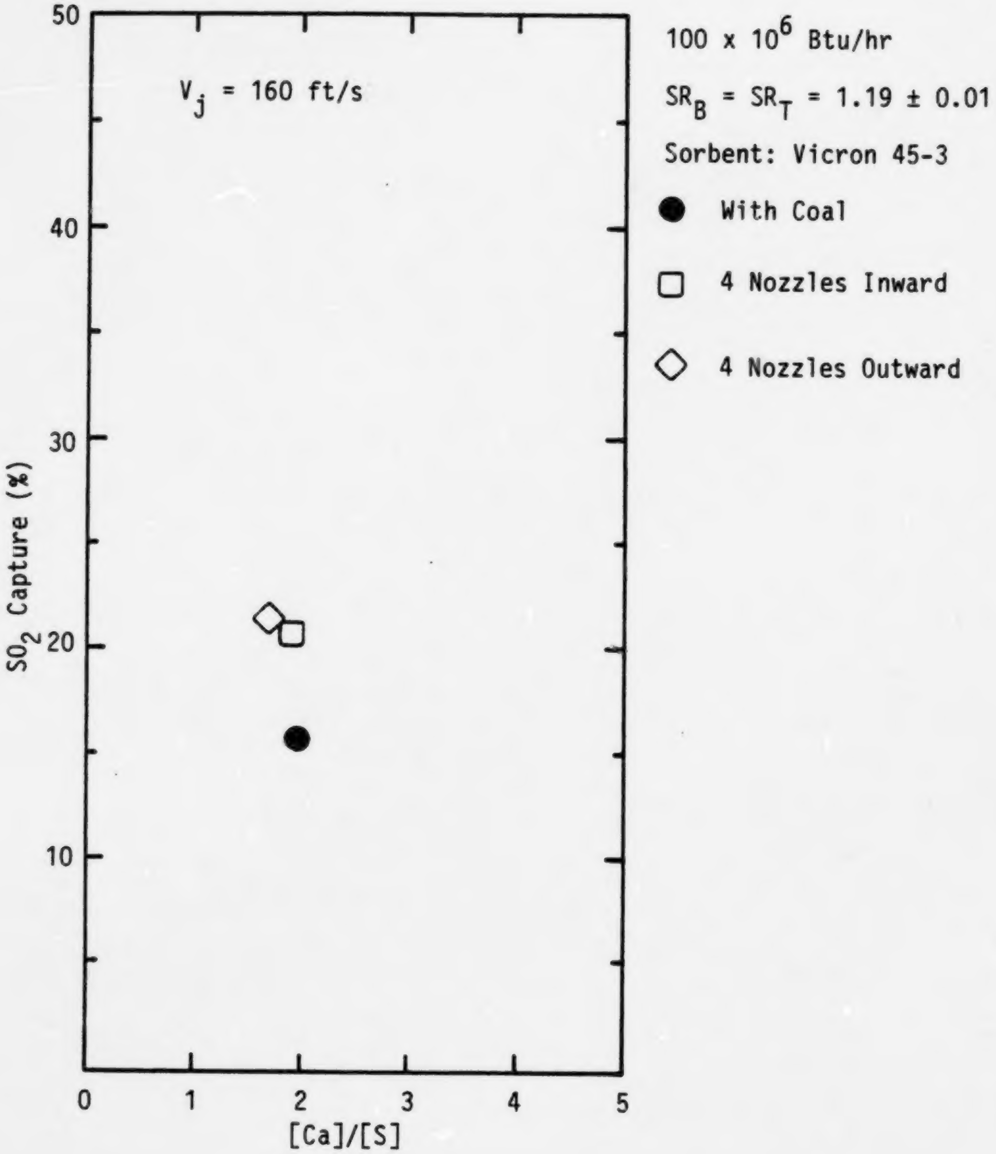


Figure 3-9. Comparison of sulfur capture -- sorbent pre-mixed with coal vs. injected through tubes in secondary air channel.

than did the premixed configuration at a Ca/S molar ratio of about 2. This may have been the result of the sorbent being exposed to slightly lower peak temperatures when the sorbent is introduced through the secondary air channel; or, the sorbent might have been less affected by mineral matter interaction in the flame region. With the special secondary-air-channel injectors, there appeared to be no clear advantage of aiming the injectors away from the flame rather than aiming them toward the flame.

The fact that SO_2 removals achieved with remote wall injection were no better than those obtained under coal/sorbent pre-mixed conditions -- where dead-burning would be expected to be severe -- suggested that, contrary to expectations, the sorbent was being exposed to high temperatures even when it was injected at Levels III and IV. Apparently, the sorbent was being drawn into the flame by recirculation eddies above the burner. To check this hypothesis, the furnace flow field was examined by visual observations.

3.2.2 Flow Visualization

Two modes of flow visualization were conducted briefly:

- Isothermal flow study in the LWS, with the LWS operating at 500 °F (air preheater operating).
- Isothermal flow study in a 1/15th scale plastic physical model of the LWS with the IS-100 burner.

The scaling criterion of constant momentum flux ratio (between the jet of sorbent and the furnace gas) was applied in simulating a non-isothermal condition with the isothermal flow case. In the LWS test, the furnace was operated with maximum available air which was preheated to the normal operating (full load) temperature (about 500 °F). Coal ash was used as a sorbent tracer; a high-intensity slit light was placed inside the LWS furnace for flow visualization. A wide range of sorbent injection velocities were investigated for Levels II to IV. Figure 3-10 summarizes the observations for these tests. The observed trajectories showed that the jets were effectively drawn down to the flame zone. Maximum jet penetration (axial distance) for all test conditions did not exceed a 1/3 of the furnace depth. This observation was consistent with observations made through the closed-circuit flame monitor during the initial SO_2 trial described in Section 3.2.1.

The results from the 1/15th-scale cold flow model showed good agreement in general with the findings in the LWS isothermal study. The model was geometrically similar to the LWS furnace, with the IS-100 burner scaled according to Thring-Newby expansion with swirl intensity correction (3). Furnace flow patterns and sorbent jet trajectories in the clear plastic model were visualized using neutrally buoyant bubbles and smoke, respectively. Figure 3-11 is a sketch of a typical two-dimensional flow pattern generated in the model at full load operating conditions. The fluid from the burner hits the back wall, creating two easily identifiable recirculating eddies above and below the burner.

The recirculation above the burner was very large, extending right up to the roof of the furnace. When the burner flow hits the rear wall of the furnace, it forms a wall jet which develops into a relatively thin layer of gas flowing up the rear wall and under the arch towards the furnace exit. This flow stagnates on the roof, with the main flow leaving the furnace exit and the recirculation flow returning down the front wall to the burner region. Sorbent jets injected from the front wall experience a downward crossflow, and will tend to be bent toward the flame region, as was also shown with the isothermal visualization tests in the LWS itself. In reviewing these flow patterns, it was seen that a suitable injection location would be from the rear sloping wall of the furnace, where the bulk of the flue gas is traveling directly towards the furnace exit. Because of the shallow depth

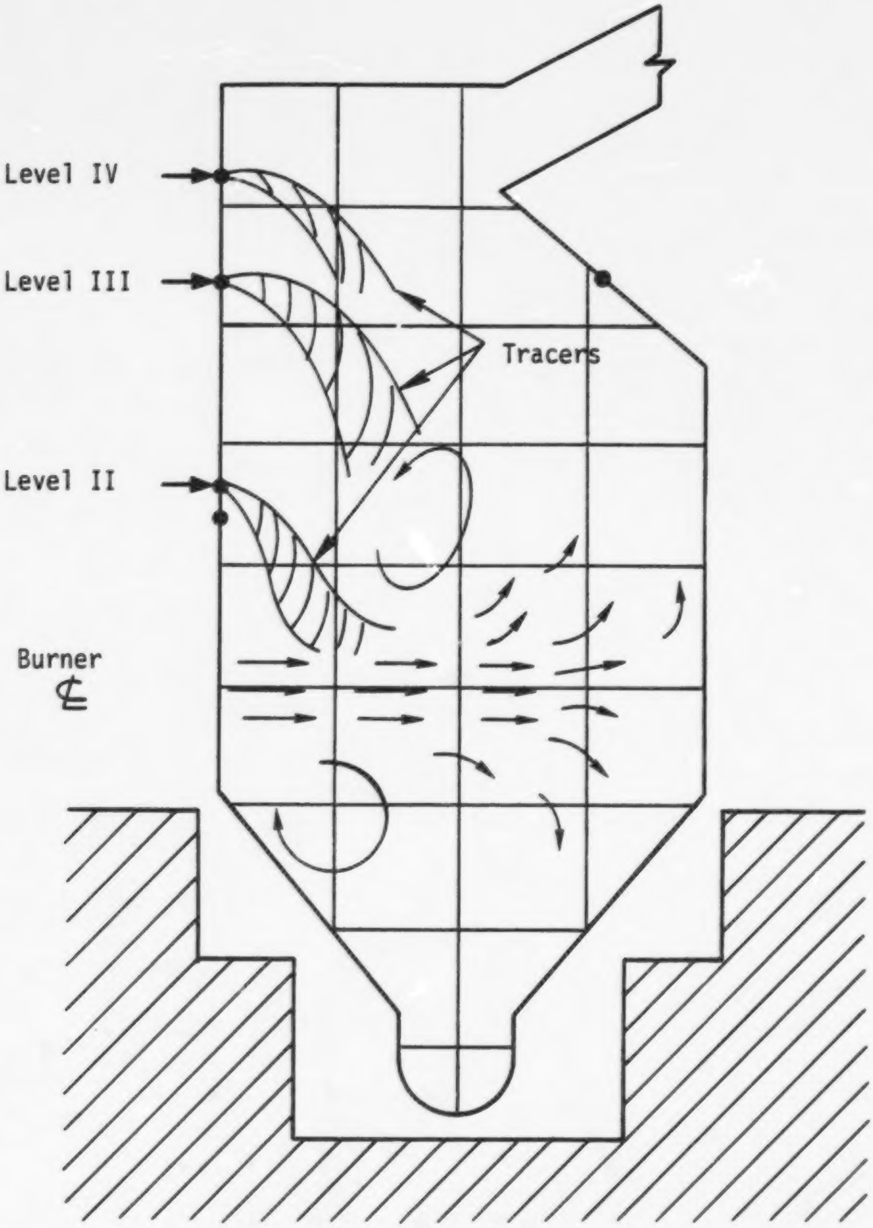

Level IV
Level III
Tracers
Level II
Burner
℄

Figure 3-10. Trajectories of tracers injected into the LWS furnace under isothermal conditions. Note that the tracers are drawn into the upper external recirculation zone near the burner exit.

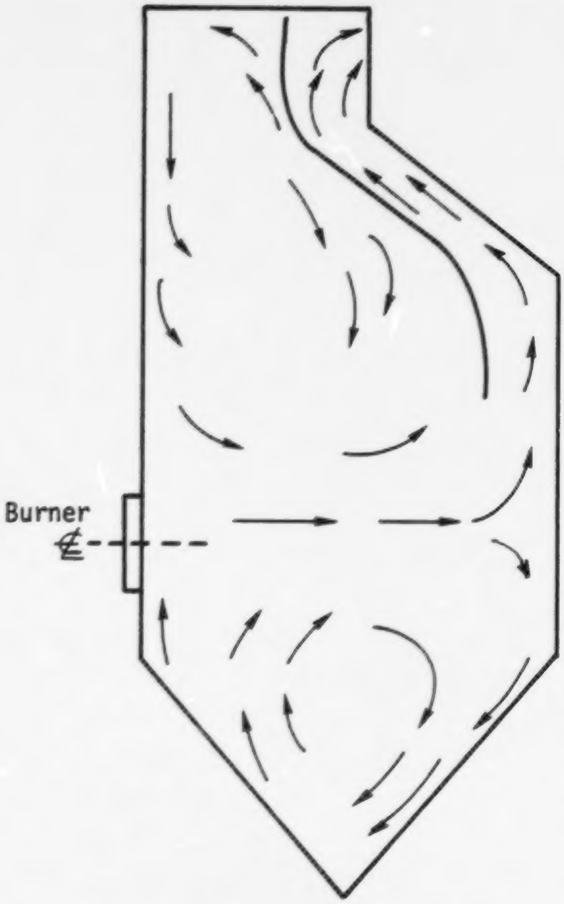


Figure 3-11. General flow pattern generated in the 1/15th-scale plastic model of the LWS by the model IS-100 burner.

of the main gas flow in this region, it would be expected that the capture might be sensitive to jet velocity, because of the risk of over-penetration of the jets, carrying the sorbent into the recirculation zone.

Alternatively, an injector location high on the front wall might prove satisfactory provided the jets were relatively "stiff" and not deflected downward very much before penetrating the width of the furnace and being entrained in the out-flowing gas stream.

Table 3-3 presents a listing of jet injection conditions and locations investigated with the isothermal plastic model. These included injection from points equivalent to Levels II, III and IV on the front wall, as well as injection from the sloping back wall opposite Level IV. The main emphasis was on smoke visualization to ascertain jet trajectories, but a limited number of cases were investigated for dispersion of sorbent using concentration measurements of tracer gas. For the tracer gas measurements, methane was injected through the jets, and methane concentration profiles were measured across the furnace exit.

Figure 3-12 shows smoke visualization of jets injected from different locations in the model. These observed trajectories are discussed qualitatively below:

Level II Injection: The jet appeared to be pulled very rapidly into the recirculation zone in the plastic model. Increasing the jet velocity in an attempt to get the jet to pass straight through the recirculation zone was not successful. The jets remained trapped in the recirculation zone and thus would be carried into the flame.

Level III Injection: At low injection velocity and at small injector diameter (i.e., jets scaled to be equivalent to a 1-inch

TABLE 3-3. SUMMARY OF TEST CONDITIONS FOR THE 1/15th SCALE ISOTHERMAL FLOW MODELING EXPERIMENT.

Run No.	Injection Location (Level)	Number of Injectors	Injector Size (Equivalent to Full-Scale, in)	Injection Velocity (ft/s)	Smoke Visualization	Tracer Measurement
1	II	2	1	160	X	-
2	IV	2	1	160	X	-
3	III	2	1	160	X	X
4	III	2	1	100	X	-
5	III	2	1	240	X	-
6	III	4	1	160	-	X
7	III	4	6	70	X	X
8	Backwall	4	1	60	-	X
9	Backwall	4	1	110	X	-
10	Backwall	4	1	150	-	-

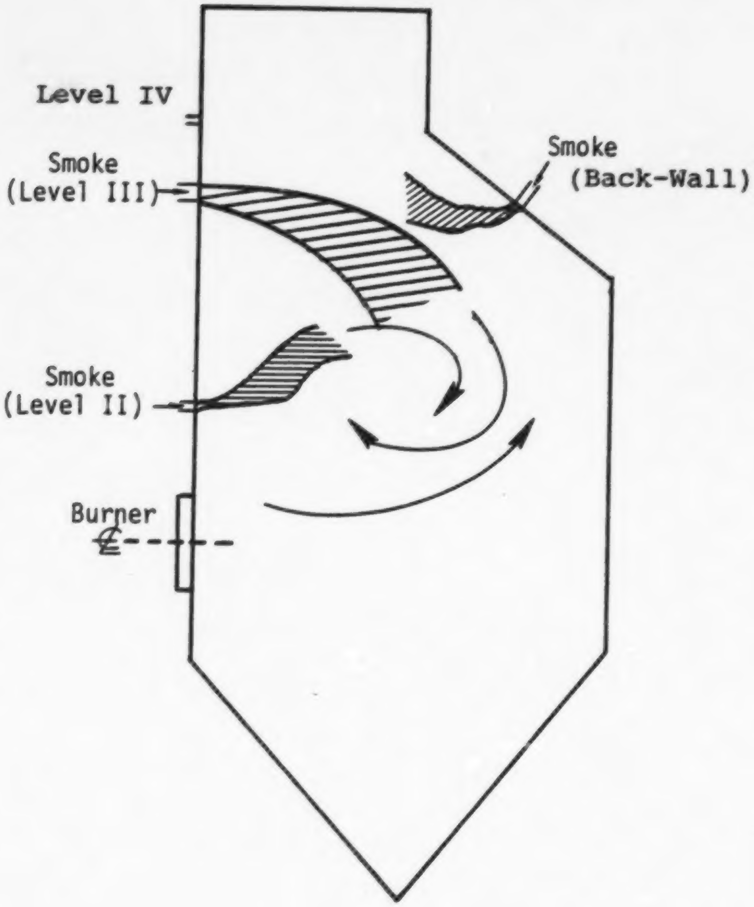

Level IV
Smoke
(Level III)
Smoke
(Back-Wall)
Smoke
(Level II)
Burner
₵

Figure 3-12. Smoke simulation of sorbent jet trajectories from various injection locations in the isothermal model.

jet in the LWS), the jet entrained rapidly into the flame zone, as shown in Figure 3-13a. Varying injection velocity V_J at constant injector size seemed to influence the jet trajectories at this injection location. Increasing jet velocity from 100 ft/s to 240 ft/s (Figures 3-13b and c) raised the jet trajectories, and slightly bypassed the recirculation zone; however, the jets still appeared to lose some fluid into the recirculation zone.

When a larger nozzle was used (i.e., a diameter equivalent to a 6-inch injector in the LWS), the jet seemed to be able to penetrate into the exiting fluid, as shown in Figure 3-13d. This penetration is attributed to the higher momentum associated with the larger jet. Nonetheless, some of the jet fluid was drawn occasionally into the recirculation zone near the furnace nose. No attempt to vary the injection velocity was made for this configuration.

Level IV Injection: At this level, the jet in the plastic model penetrated across to the furnace nose and was entrained into the exit flow. The jet did not appear to lose much fluid into the recirculation zone. This result differs from the observed jet path in the LWS 500 °F isothermal tests, where the jets were pulled downward into the recirculation flow. This difference in the results may have been caused by small differences in flow pattern in this region between the plastic model and the LWS furnace. The LWS sulfur capture results with sorbent injection at this level show poor capture, supporting the conclusion that, during combustion in the LWS, the Level IV jets were carried down into the flame zone.

Back-wall Injection: Trajectories for jets injected from the sloping rear wall of the plastic model at Level IV are presented in Figure 3-14. The sketch illustrates jet trajectories for different injection velocities. At low velocity (60 ft/s), the jet

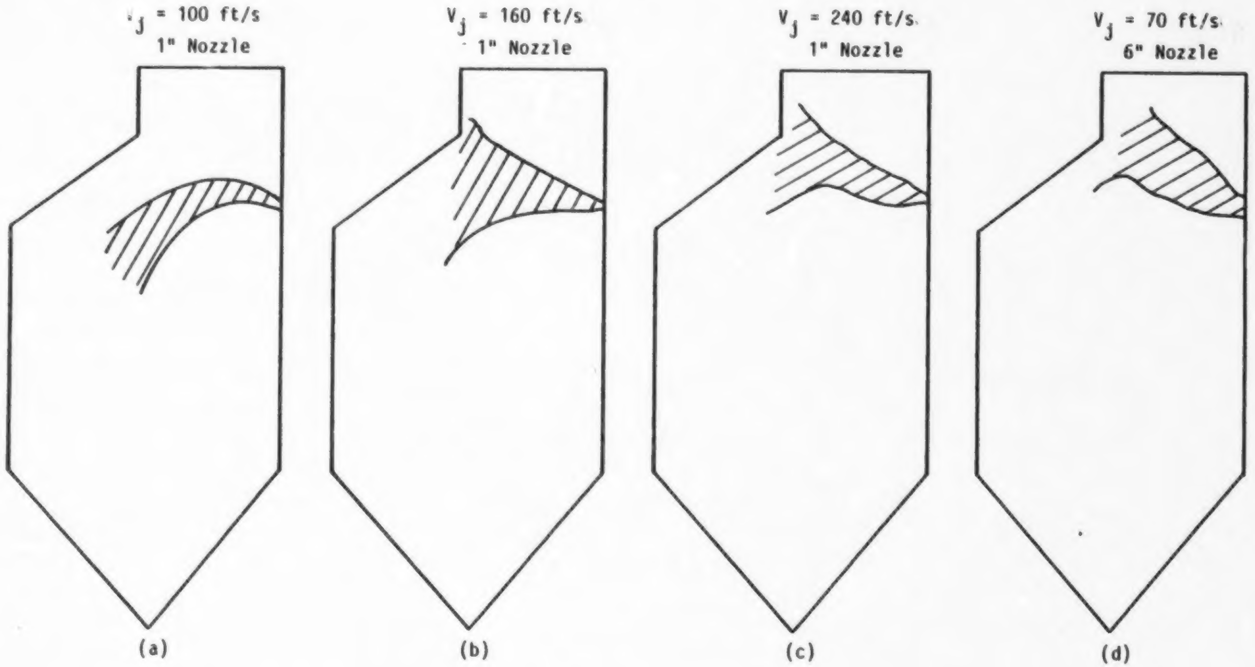

V_j = 100 ft/s
1" Nozzle
V_j = 160 ft/s
1" Nozzle
V_j = 240 ft/s
1" Nozzle
V_j = 70 ft/s
6" Nozzle
(a)
(b)
(c)
(d)

Figure 3-13. Jet trajectory sketches showing effect of injection velocity and injector diameter at Level III front-wall injection location (based upon testing in plastic model).

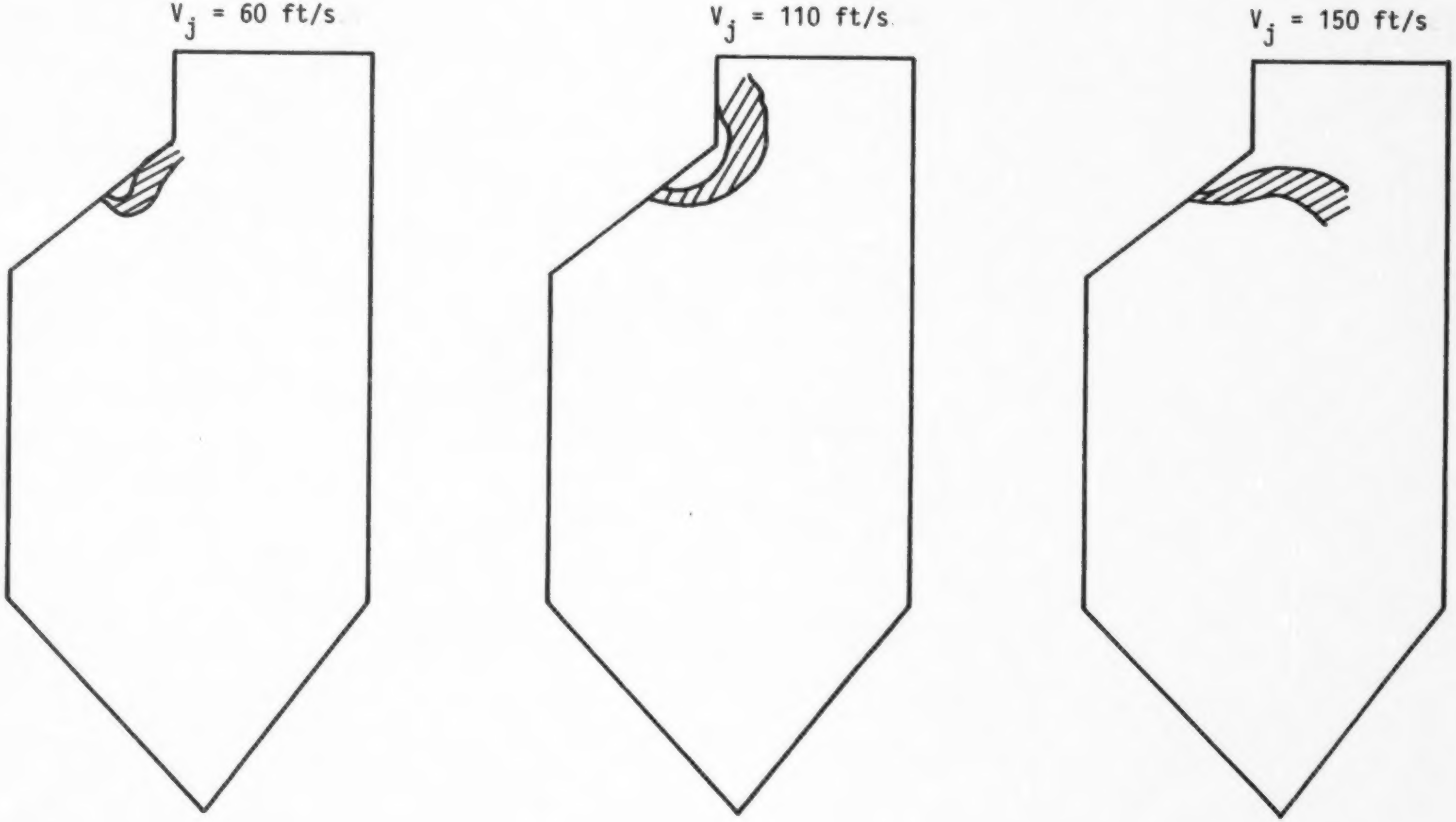
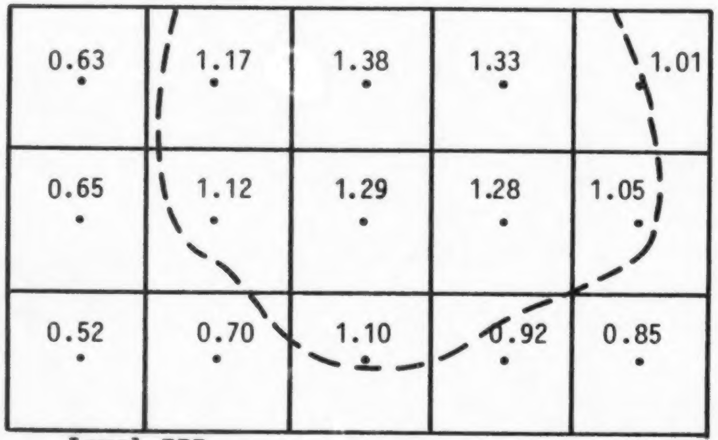

V_j = 60 ft/s
V_j = 110 ft/s
V_j = 150 ft/s

Figure 3-14. Jet trajectory sketches showing effect of injection velocity at back wall injection location (based upon testing in plastic model).

was pushed back against the nose of the furnace by the ascending fluid, as illustrated in the left-hand figure; thus, poor mixing would be expected. At high velocity (150 ft/s), the jet penetrated rapidly into the recirculation zone, resulting in the sorbent being carried into the flame (right-hand figure). The best mixing pattern for injecting from the back-wall was found with a medium injection velocity (about 110 ft/sec). Verification of this observation on SO_2 capture is discussed in detail in Section 3.2.4.

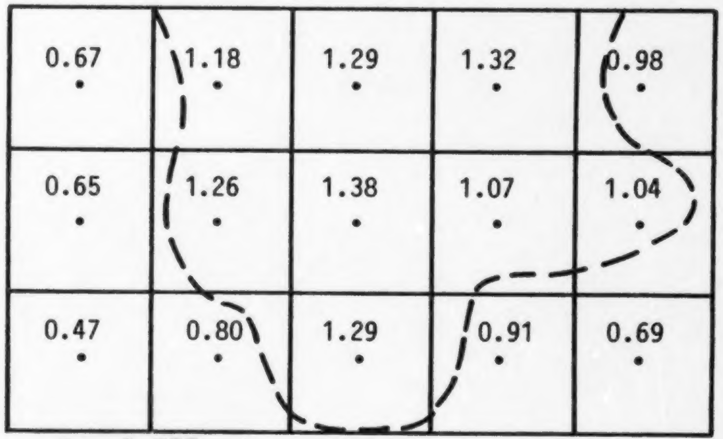
These smoke visualization tests showed that the best prospects for good SO_2 capture would be with jet configurations where the bulk of the jet fluid would be able to pass directly to the furnace exit without being carried into the flame zone on the way. The most promising injection locations would appear to be: 1) the back wall, opposite Level III; or 2) perhaps Levels III and IV on the front wall with large, high momentum jets having enough "stiffness" to avoid being substantially entrained into the recirculation zone. To further characterize prospective jet configurations at these locations, measurements of jet dispersion at the furnace exit were made in the plastic model using methane gas as a tracer for the jet fluid.

Figure 3-15 shows the methane results for four injection configurations, three involving injection at Level III on the front wall, and the fourth involving injection on the back wall. The results are presented in the form of a grid representing the vertical cross-section of the furnace exit (i.e., looking horizontally into the furnace exhaust duct). In each cell of the grid, a number is presented representing the ratio of the local methane concentration in that cell (C_L) to the concentration that would have existed if all of the methane injected through the jets had been well-mixed across the exit cross-section (C_{WM}). The broken line in each of the four sketches represents the contour where the ratio $C_L/C_{WM} = 1.0$.



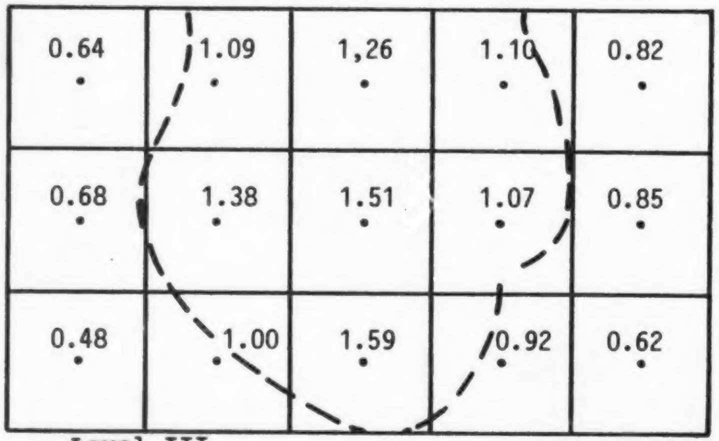
0.63	1.17	1.38	1.33	1.01
0.65	1.12	1.29	1.28	1.05
0.52	0.70	1.10	0.92	0.85

Level III
a) 2 x 1" Nozzle, V_j = 160 ft/sec, COV = .28



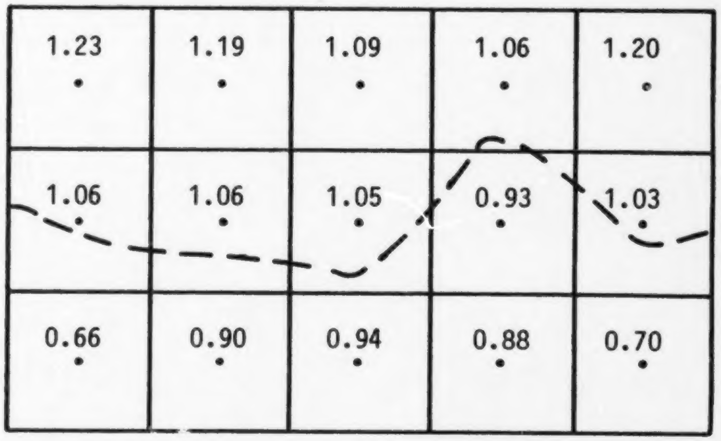
0.67	1.18	1.29	1.32	0.98
0.65	1.26	1.38	1.07	1.04
0.47	0.80	1.29	0.91	0.69

Level III
b) 4 x 1" Nozzle, V_j = 160 ft/sec, COV = .29



0.64	1.09	1,26	1.10	0.82
0.68	1.38	1.51	1.07	0.85
0.48	1.00	1.59	0.92	0.62

Level III
c) 4 x 6" Nozzle, V_j = 70 ft/sec, COV = .33



1.23	1.19	1.09	1.06	1.20
1.06	1.06	1.05	0.93	1.03
0.66	0.90	0.94	0.88	0.70

d) 4 x 1" Nozzle, V_j = 110 ft/sec Backwall injection, COV = .17

Figure 3-15. Degree of mixing of sorbent at the vertical furnace exit plane (looking horizontally into the furnace exhaust duct). Based upon methane tracer testing in the plastic model.

The closer the number in a given cell is to 1.0, the more uniformly mixed the methane is at that point. The Coefficient of Variation (COV) is one measure of how uniformly the methane is mixed across all of the cells in the cross-section for any one of the four sketches. The COV is the standard deviation divided by the mean of the 15 sample points (cells). The lower the COV, the more uniformly the tracer is mixed for that particular injection configuration.

The dispersion patterns for the three Level III front-wall injection alternatives (Figures 3-15a, b, and c) are remarkably similar. In all cases, there is a region in the center of the furnace exit opening having higher than average concentrations, while the outer region has somewhat lower concentrations. There is little difference between using 2 versus 4 injectors, or between large versus small injectors. This suggests that these jets are mixing partly be being drawn through the recirculation zone into the main burner region, which is turbulent enough to ensure rapid mixing. The Coefficient of Variation was about 0.3 for each of these three Level III cases; this is considered to be reasonably good mixing.

The methane dispersion pattern for the rear-wall injection case (Figure 3-15d) shows very uniform mixing across the width of the furnace exit, with some limited variation over the height of the furnace opening. The COV was only 0.17, which represents very uniform dispersion. The lower concentration at the bottom of the opening results from the separation of the exit flow as it turns around the nose. This is shown in Figure 3-16, which illustrates the flow pattern in the upper furnace region in more detail than is shown in Figure 3-11.

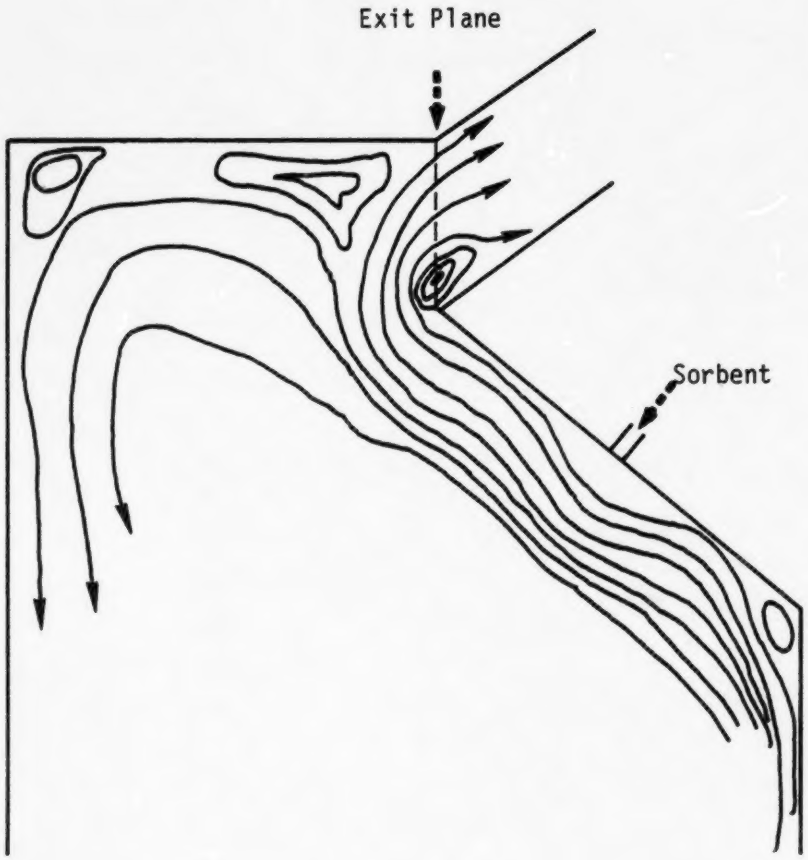

Exit Plane
Sorbent

Figure 3-16. Detail of upper furnace flow field.

In summary, these isothermal model tests showed that the LWS furnace flow with the IS-100 burner is characterized by a large recirculation zone adjacent to the front wall above the burner, with the main furnace gas exit flow passing in a relatively thin layer up the rear wall of the furnace. Smoke visualization of injection configurations showed that jets injected from the front wall were likely to be swept down into the flame by the recirculation flow unless they had high momentum (i.e., a sufficiently high velocity and/or mass) and were thus "stiff" enough to resist significant deflection by the recirculation flow. Jets injected from the rear, sloping wall were directly entrained into the outgoing furnace flow, and would disperse effectively without being drawn into the flame provided that their velocity was appropriately selected.

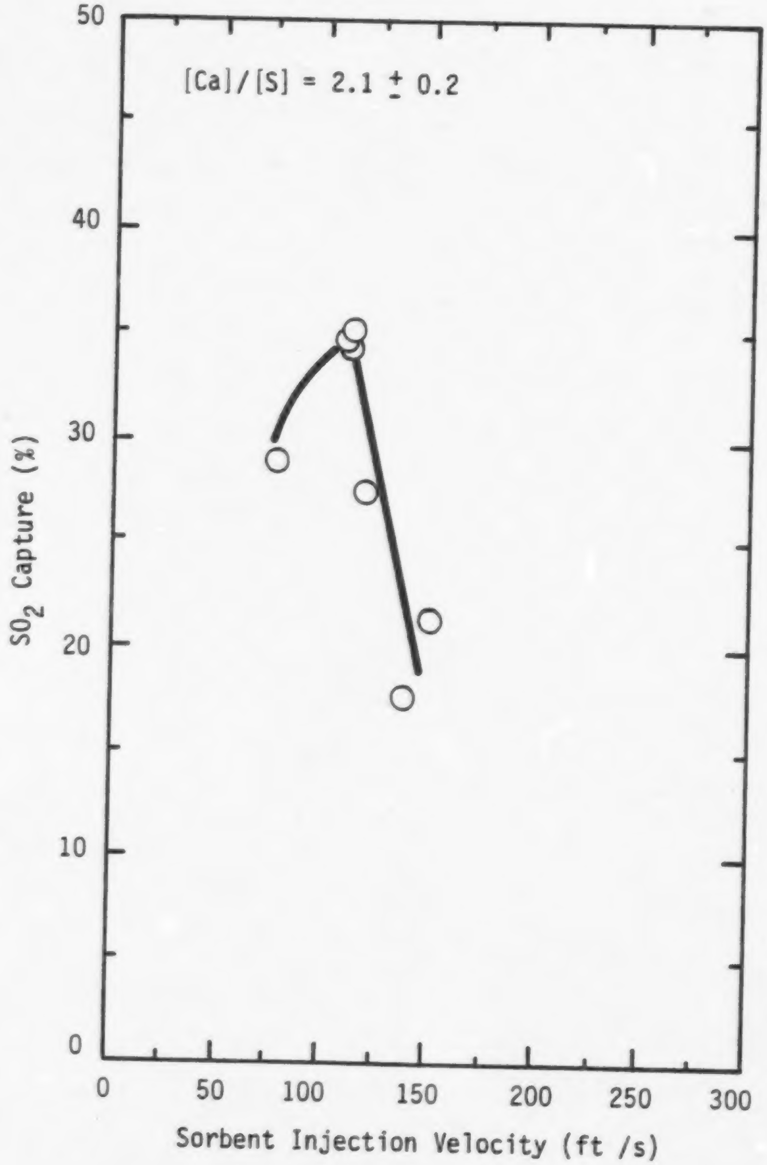
As a result of these isothermal flow results and of the poor SO_2 capture performance during the initial LWS combustion tests, it was decided to investigate rear-wall injection of sorbent in the LWS.

3.2.3 Effect of Sorbent Injection Parameters -- Back-Wall Injection (Vicron Limestone)

Following the cold flow studies, tests were conducted with sorbent injection from a back-wall location, since this was the location which appeared to offer the greatest potential. Vicron 45-3 limestone was the sorbent used for this testing. A bank of 4 injectors (each 1 inch in diameter) was placed in the sloping back wall, close to the nose of the LWS furnace. These back-wall injectors were at approximately the same furnace elevation as the Level III injection location (the OFA ports) on the opposing front wall. The back-wall injectors were installed perpendicularly to the wall of the nose, forming an angle of 53° downward from the horizontal plane, as suggested in Figure 3-12.

Tests were conducted to determine the effect of injection velocity V_j and calcium-to-sulfur ratio on SO_2 capture with Vicron injected at the back-wall location. Figure 3-17 shows the influence of sorbent injection velocity on SO_2 capture with Ca/S = 2.1. Although the data are scattered, there is a distinct peak in the curve, indicating an optimum injection velocity for this injection configuration of about 115 ft/s. This variation of capture with velocity is consistent with the observed furnace flow pattern, and with the smoke trajectories seen for this injection configuration in the plexiglass model. With high injection velocity, the sorbent jets penetrate through the relatively narrow layer of gas flowing up the rear wall toward the exit, and the sorbent is carried into the flame zone by the recirculating flow deeper in the furnace. With low injection velocity, the jets are bent over against the rear wall of the furnace by the up-flowing layer, and the sorbent does not disperse adequately into the furnace gas before leaving the furnace. But with an intermediate velocity, the sorbent disperses through the up-flowing layer without penetrating into the interior recirculation zone.

Figure 3-18 shows the SO_2 capture as a function of calcium-to-sulfur molar ratio with back-wall injection of Vicron, for jets having the optimum velocity of 115 ft/s. The SO_2 capture increases rapidly with increasing Ca/S ratio, but approaches its limit at a Ca/S of about 3. SO_2 capture at Ca/S = 2 is about 36 percent. Also shown on Figure 3-18 for comparison is the SO_2 capture obtained with injection through the front wall at the same elevation (Level III) using 4 one-inch injectors and an injection velocity of 160 ft/s. Level III front-wall injection shows SO_2 capture of 23 percent at Ca/S = 2, significantly lower than achieved with rear-wall injection. Apparently, the high injection velocity used at the front-wall location was not sufficient to avoid entrapment of the sorbent in the recirculation zone, and hence the sorbent performance was reduced by exposure to high temperatures.



100 x 10^6 Btu/Hr

$SR_B = SR_T = 1.20 \pm 0.01$

Injector ID = 1"

Number of Injectors = 4

Injection Location = Back Wall

Sorbent = Vicron

Figure 3-17. Effect of back wall injection velocity on SO_2 capture.

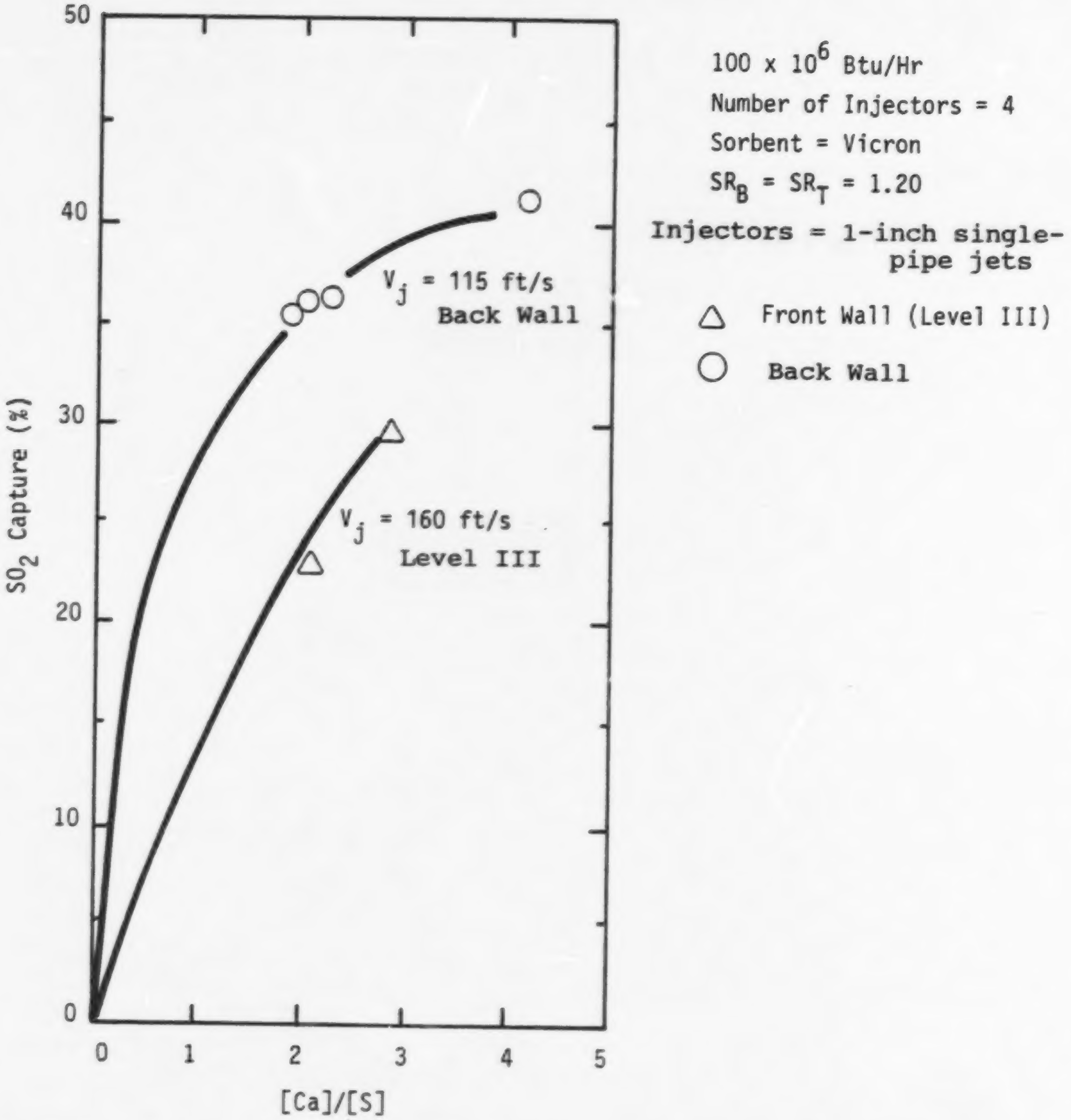


Figure 3-18. Comparisons of SO_2 reductions with front wall vs. back wall injection location -- 1-inch single-pipe jets.

3.2.4 Effects of Sorbent Injection Parameters -- Front-Wall Injection (Vicron Limestone)

The isothermal studies generally showed that sorbent injected from the front wall would be drawn into the recirculation zone and carried towards the flame. However, high-momentum (or "stiff") jets might still largely penetrate the recirculation zone, and thus might carry a large proportion of the sorbent through to the furnace exit flow without being passed through the flame. Thus it was expected that injection parameters could have a significant effect on overall SO_2 capture. Parameters of particular significance would be injection velocity V_j and jet diameter; these parameters both influence the jet momentum, and thus the shape of the jet trajectory. Another parameter of possible importance could be jet design, specifically, the use of double concentric jets; the outer air sheath in such jets could help improve capture by protecting the sorbent, minimizing entrainment of the sorbent into the recirculation zone as the jets pass through this zone. (Double concentric jets also have high mass, by virtue of the air sheath, and hence higher momentum to push the sorbent through the recirculation zone.)

Near-Burner Injection

Figure 3-19 shows SO_2 capture versus Ca/S ratio with Vicron limestone for a range of injection configurations close to the burner. These configurations include injection of the sorbent premixed with the coal, and injection of sorbent through tubes in the secondary air channel, as shown previously in Figure 3-9. Figure 3-19 also shows results with injection through two injectors at Level II, using different jet diameters (1 and 2.5 inches) and different injection velocities (60 to 240 ft/s). None of the Level II injection configurations tested here gave SO_2 captures that were any better than the low captures obtained when the sorbent was pre-

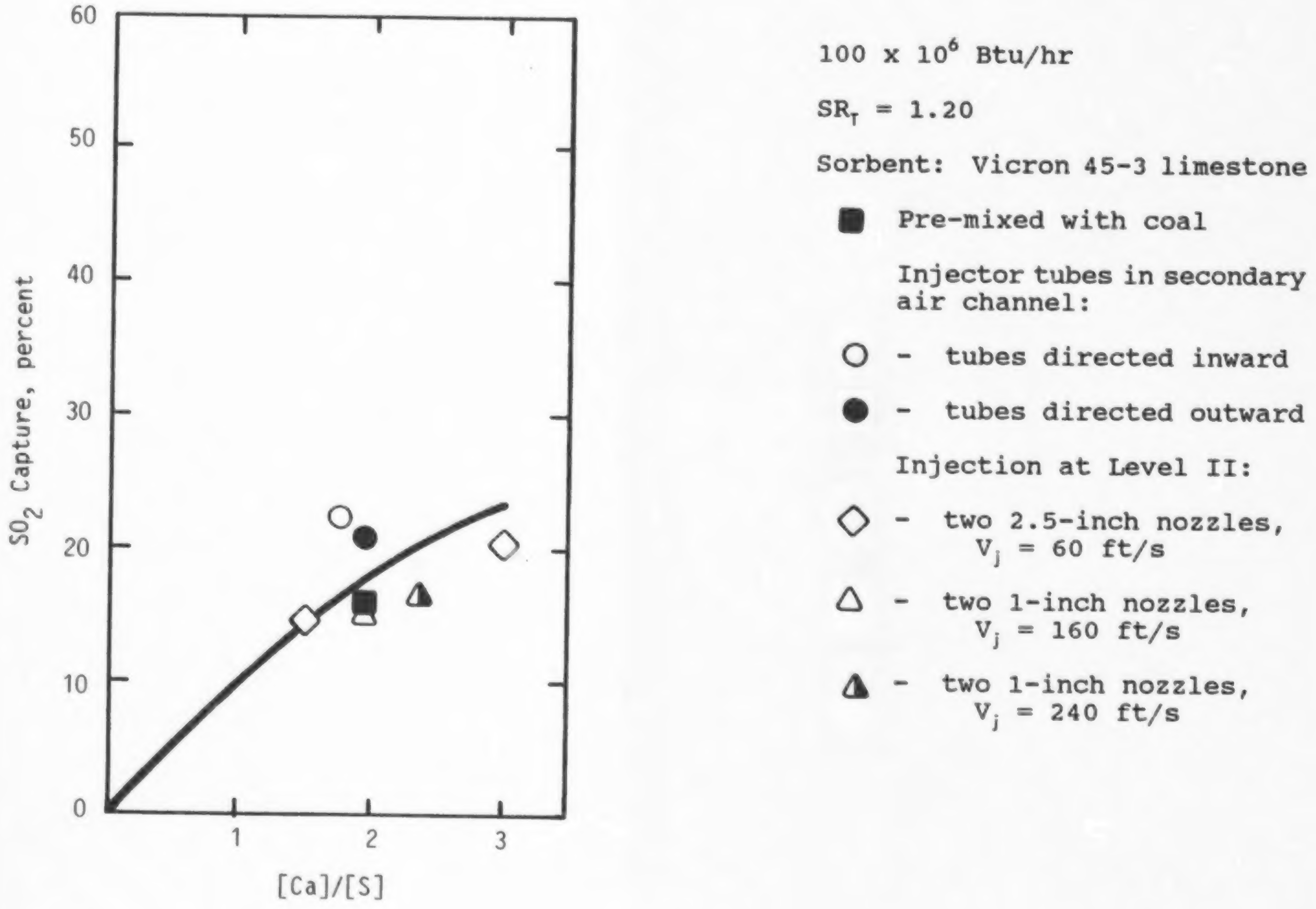


Figure 3-19. Effect of injection parameters on SO_2 capture for near-burner injection.

mixed with the coal or injected through the secondary air channel. There was no apparent influence of jet diameter or velocity. This result is consistent with the observations from the isothermal model tests, which suggested that sorbent injected at this level is rapidly entrained into the burner flow regardless of jet momentum, leading to sorbent overheating and loss of reactivity.

Level IV Injection

Figure 3-20 shows SO_2 capture versus Ca/S ratio for injection of Vicron at Level IV (19 ft above burner centerline) for a range of sorbent jet velocities. Based upon the cold modelling studies, it was thought that injection at this location might push the sorbent through the recirculation zone into the LWS exhaust duct if the jets had sufficient momentum. Not many tests were conducted for injection at this level, and the results do not follow the anticipated pattern. It would have been anticipated that, if anything, higher jet velocities would have improved capture by penetrating the sorbent through the recirculation zone; however, as seen in the figure, the best sorbent performance was observed in the one run at lowest velocity (110 ft/s). At the higher velocities (160 and 250 ft/s), captures were generally low (in the range of 10 to 20 percent at Ca/S = 2), suggesting that the sorbent was being drawn down toward the flame zone and being deactivated even at these higher jet velocities. Entrapment of Level IV jets into the recirculation zone in this manner would be predicted based upon the LWS 500 °F isothermal visualization (Figure 3-10), but would not necessarily be predicted from the plexiglass cold-model testing. At this level in the LWS, the furnace flow is turbulent and complex, and probably sensitive to conditions in the lower furnace, as was demonstrated by the differences between jet trajectories observed in the LWS and its cold model. Thus, small changes in furnace input conditions could lead to shifts in the upper furnace flow that could produce inconsistent SO_2 captures, masking

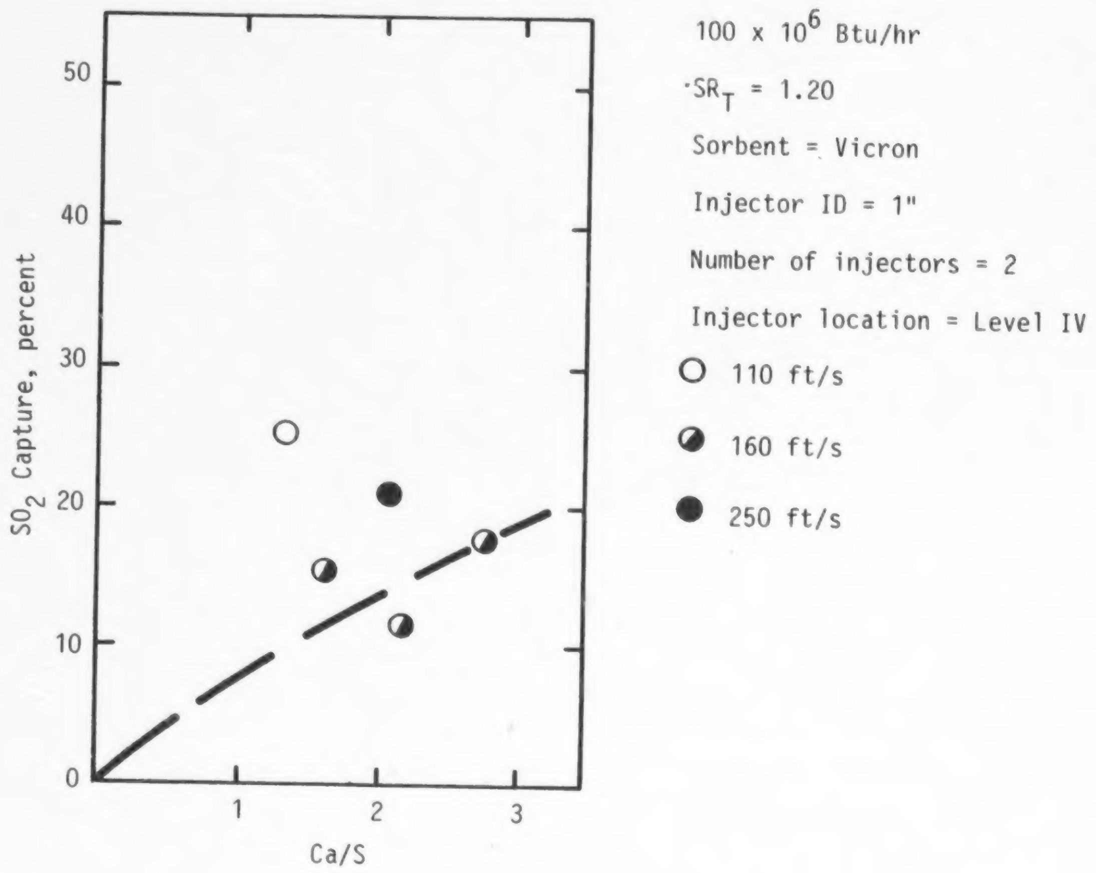


Figure 3-20. Effect of injection velocity on SO_2 capture for injection at Level IV.

the effects of injection velocity (and giving the apparently anomalous results observed at the lower injection velocity).

Level III Injection

Figure 3-21 shows SO_2 capture with Vicron as a function of Ca/S ratio for 1-inch diameter jets at Level III on the front wall. Tests were conducted with two different jet configurations: a) all 4 jets, across the furnace width; and b) only 2 jets (i.e., the inner pair of the four jets at this location). Jet velocity was also varied. When using all 4 jets, little influence of jet velocity was observed, and overall SO_2 capture was low (22 percent at Ca/S = 2). This is consistent with the sorbent being trapped in the recirculation zone on the front wall. When only the 2 inner jets were used, capture was comparable to that achieved with 4 jets when the 2 jets were operated at high velocity (240 ft/s); however, capture was lower when the two jets were at lower velocity, showing a velocity effect not seen in the 4-jet case. This different behavior with 2 jets is thought to result from differences in the strength of the recirculation zone across the width of the furnace. Down-flow velocities are likely to be lower towards the sides of the furnace because of the influence of the side walls. Thus, a larger proportion of the sorbent in the outer jets might be expected to reach the exit gas flow without being drawn into the flame region. This could give higher overall capture for the 4-jet cases, as well as making them less sensitive to jet injection velocity, since nominally half of the sorbent is injected through the outer ports when 4 jets are used.

Figure 3-22 shows SO_2 capture versus Ca/S ratio using four 6-inch diameter single-pipe jets at Level III. In these tests, the sorbent was mixed with overfire air, and injected through the 6-inch OFA ports. Jet velocity was varied over the range of 15 to 70 ft/s; jet velocity was limited by the need to limit SR_{OFA} to 5

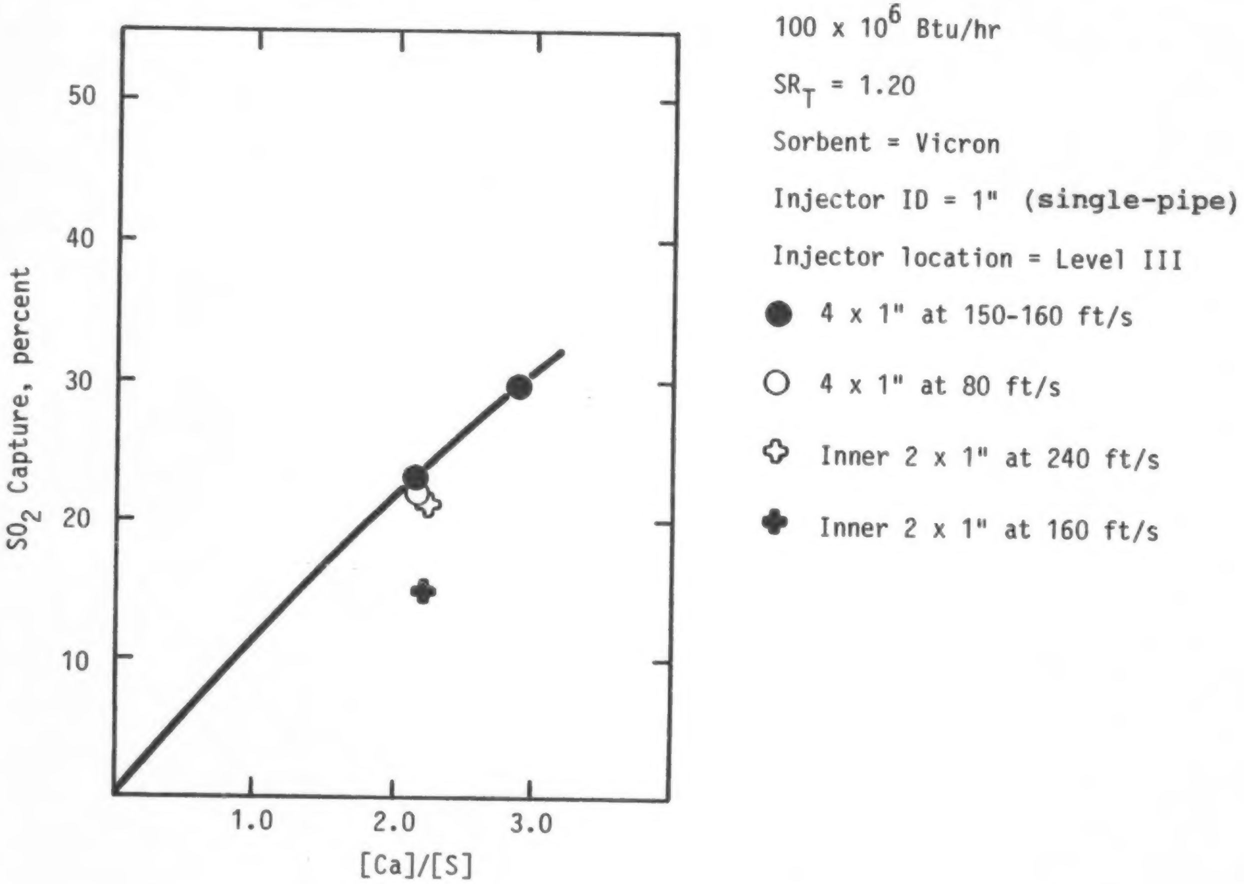


Figure 3-21. Effect of number of jets and injection velocity on SO_2 capture for injection at Level III.

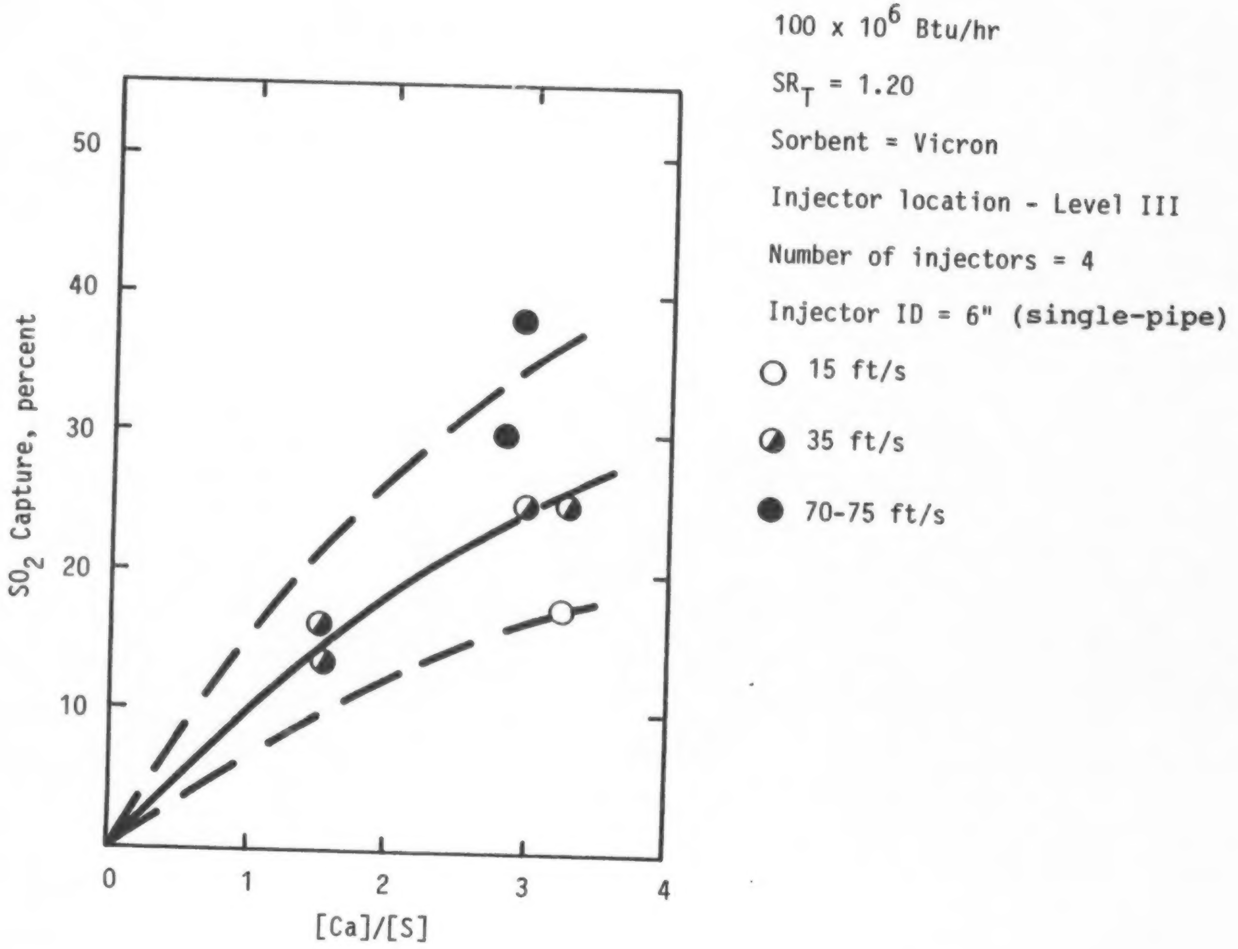


Figure 3-22. **Effect of injection velocity for 6-inch single-pipe jets located at Level III.**

percent of the total air (SR_T). Although the injection velocities used were lower with these larger jets, their overall trajectories were expected to be similar to the small, high velocity, jets (based on empirical correlations for jet trajectories), due to the large mass of the 6-inch jets. The results in the figure show a consistent influence of velocity, with SO_2 capture increasing as jet velocity increases. These larger jets mix more slowly with the furnace gas compared with the small jets; hence, it can be expected that the high-velocity (and therefore less-deflected) jets would pass more sorbent into the exit gas without the sorbent passing through the flame region. This is also supported by the comparison between Figures 3-21 and 3-22, which shows that the 6-inch jets at 75 ft/s gave somewhat higher capture than the 1-inch jets at 160 ft/s (25 percent at Ca/S = 2, compared to 20 percent).

Double Concentric Jet Injection

Double concentric jet injection was tested at Level III using a 1-inch diameter sorbent jet along the axis of the 6-inch diameter OFA jets. The concept of double concentric jets had been tested in previous programs, as well as Phase 1 of this program (Reference 1); such jets had been found under some circumstances to give improved capture compared to simple single-pipe jets. The reason for possible improved capture is believed to be that the interior sorbent jet is protected (by the sheath of air in the outer, annular air jet) from mixing with high temperature furnace gas until the sorbent has been transported into cooler flue gas. This would seem to be particularly useful for near-burner injection locations, to help avoid overheating of the sorbent.

In these investigations, injection in a double concentric mode at Level III was found to be beneficial. Figure 3-23 shows a comparison between the SO_2 capture obtained using simple, single-pipe 6-inch sorbent jets, and using 1-inch sorbent jets in a 6-inch

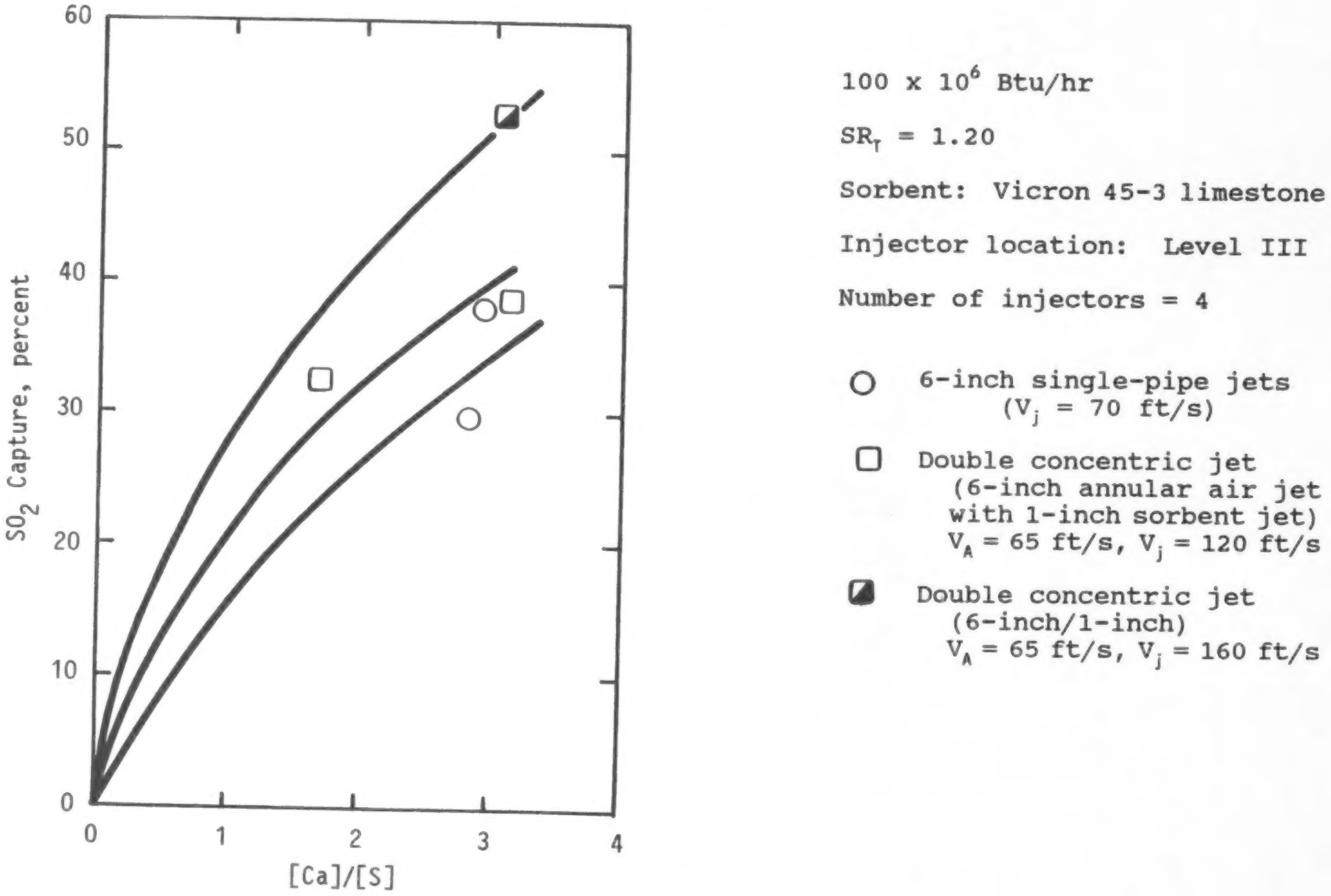


Figure 3-23. Effect of sorbent injection using 6-inch double-concentric jets vs. 6-inch single-pipe jets at Level III.

annular air jet (double concentric mode). In all cases, the velocity in the 6-inch pipe -- i.e., the sorbent jet velocity V_j in the single-pipe case, or the annular air velocity V_A in the double concentric case -- was about 65-70 ft/s. In the double concentric case, two different velocities were used in the 1-inch sorbent jet (120 and 160 ft/s). Figure 3-23 shows that the double concentric jets gave higher SO_2 capture (up to 41 percent at Ca/S = 2). Furthermore, the capture improved as the inner (sorbent) jet velocity was increased. Since the single-pipe jet and both double concentric jets have essentially the same initial momentum flux, and hence the same overall crossflow trajectory, the explanation for this improved capture seems to be improved protection of the sorbent as it passes across the recirculation zone above the burner. With the double concentric jet, the sorbent is concentrated on the jet axis, and is the last jet material to be entrained by the crossflow gas. Hence, in the double concentric case, the sorbent is more likely to be transported across the recirculation zone into the exit gas flow.

Figure 3-24 shows SO_2 capture for double concentric jets, with a comparison between using all 4 injectors or only the 2 middle injectors. As seen earlier with the 1-inch single-pipe jets (Figure 3-21), there is an improvement when 4 double concentric jets are used instead of 2. As with the single-pipe jets, this advantage for 4 injectors over 2 is thought to be the result of the lower down-flow velocities that might be expected near the walls, where half of the sorbent is injected in the 4-injector case; the sorbent injected near the walls might be somewhat less likely to be drawn into the flame zone. The advantage of 4 injectors is not thought to be due to improvements in overall dispersion caused by the larger number of injectors. As shown before (in Figure 3-23), an increase in the 1-inch sorbent jet velocity brought an increase in capture with the double concentric jets, for a given number of jets.

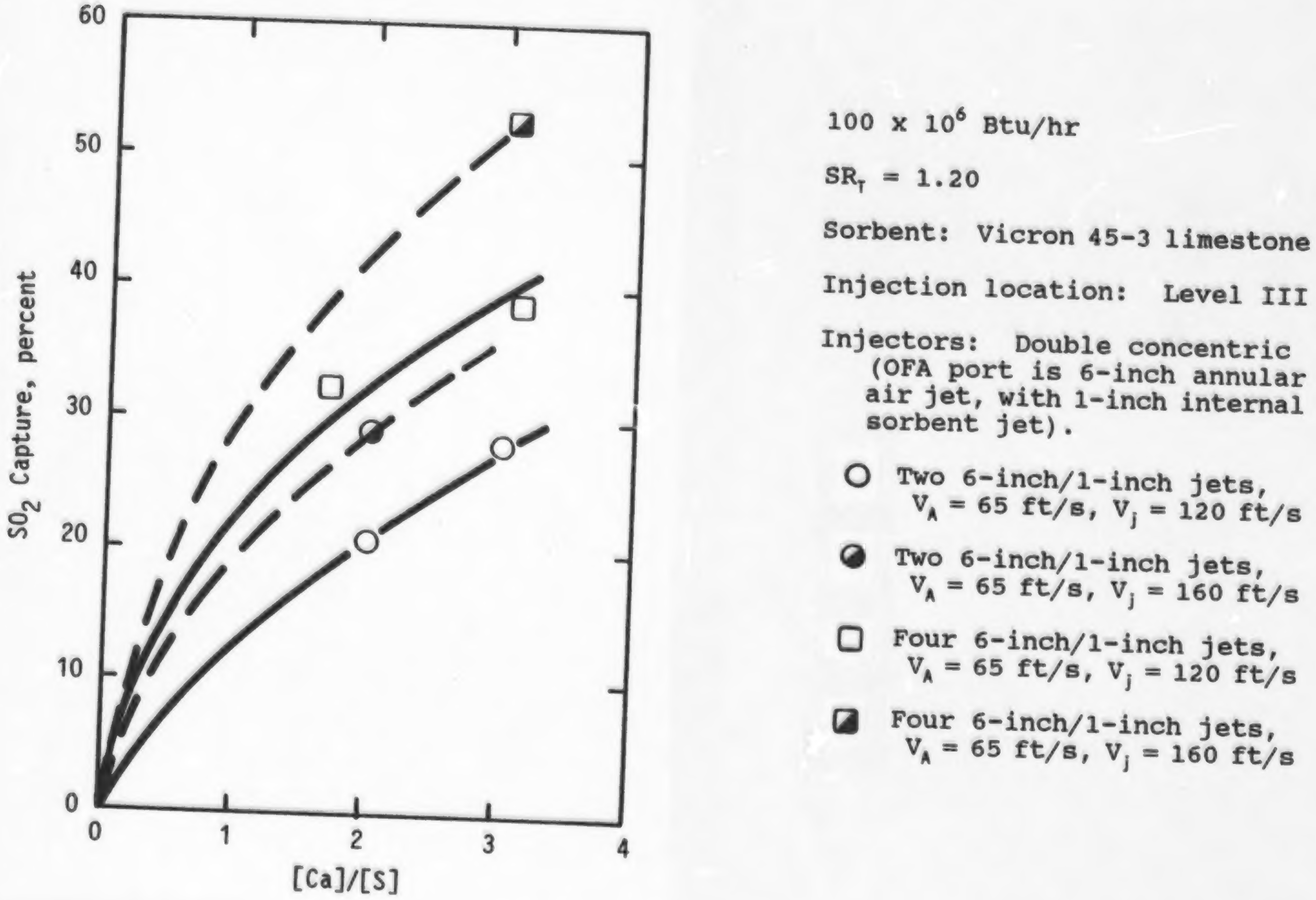


Figure 3-24. Sorbent injection using double-concentric jets at Level III -- effect of sorbent jet velocity and of number of injectors.

These front-wall injection tests showed that reasonable SO_2 capture from front-wall injection could only be obtained at Level III with large double concentric jets at relatively high velocities. This is considered to be a consequence of the complex flow field in the LWS furnace, which causes a significant proportion of the sorbent to be drawn into the flame zone and overheated, even though the gas temperature at the injection location itself is below the temperature at which sorbent sintering and deactivation is thought to occur. At the highest velocities used, the front-wall double concentric jets gave better captures than the smaller diameter rear-wall injectors.

All of the sorbent injection tests reported above have been with Vicron 45-3 limestone. Following this investigation of jet parameters using Vicron, both the back-wall 1-inch jets and the Level III front-wall double concentric jets were used to investigate the influence of alternative sorbent types.

3.2.5 Effect of Sorbent Type

Three different sorbents were tested with the most promising configurations at both the front- and back-wall locations. The sorbents used were Vicron, the baseline limestone used for the previous investigations; a dolomite, identified as D3002; and a pressure-hydrated dolomitic lime (PHDL), commonly known as Type S lime.

The front-wall injection configuration used involved the 4 double concentric injectors at Level III (1-inch sorbent jet inside a 6-inch annular air jet). The sorbent was supplied through the inner 1-inch jet at a velocity of about 150 ft/s. The outer 6-inch annular jet was supplied with overfire air at a velocity of 65 ft/s. These were the jets which gave the best capture among the front-wall injection configurations tested. Figure 3-25 shows the SO_2 capture as a function of Ca/S ratio for each of the three sorbents with the double concentric jets. The highest capture was obtained with the pressure-hydrated dolomitic lime, which yielded an SO_2 removal of 62 percent at Ca/S = 2. The next most reactive sorbent was the dolomite, giving 45 percent SO_2 removal at Ca/S = 2. In this test series, Vicron performed surprisingly well, with slightly above 40 percent removal at Ca/S = 2. This ranking is consistent with previous experience with these different sorbents: dolomite has commonly been found to give higher capture than limestone at the same calcium-to-sulfur ratio, and the pressure-hydrated dolomitic lime has been found to be superior to the raw dolomite.

The back-wall injection configuration used the 4 one-inch injectors located on the sloping wall at the underside of the furnace arch (approximately opposite Level III). The sorbent jet velocity through these injectors was 116 ft/s, which was the optimum identified earlier for that location (see Figure 3-17). Figure 3-26 shows the SO_2 capture for the three sorbents with this injection configuration. In this case, the dolomite and the pressure hydrate appear to give very similar SO_2 capture, in the range of 50-60 percent at Ca/S = 2. The Vicron gave lower capture than the other two sorbents, as expected, and slightly lower capture than was obtained with Vicron during front-wall injection.

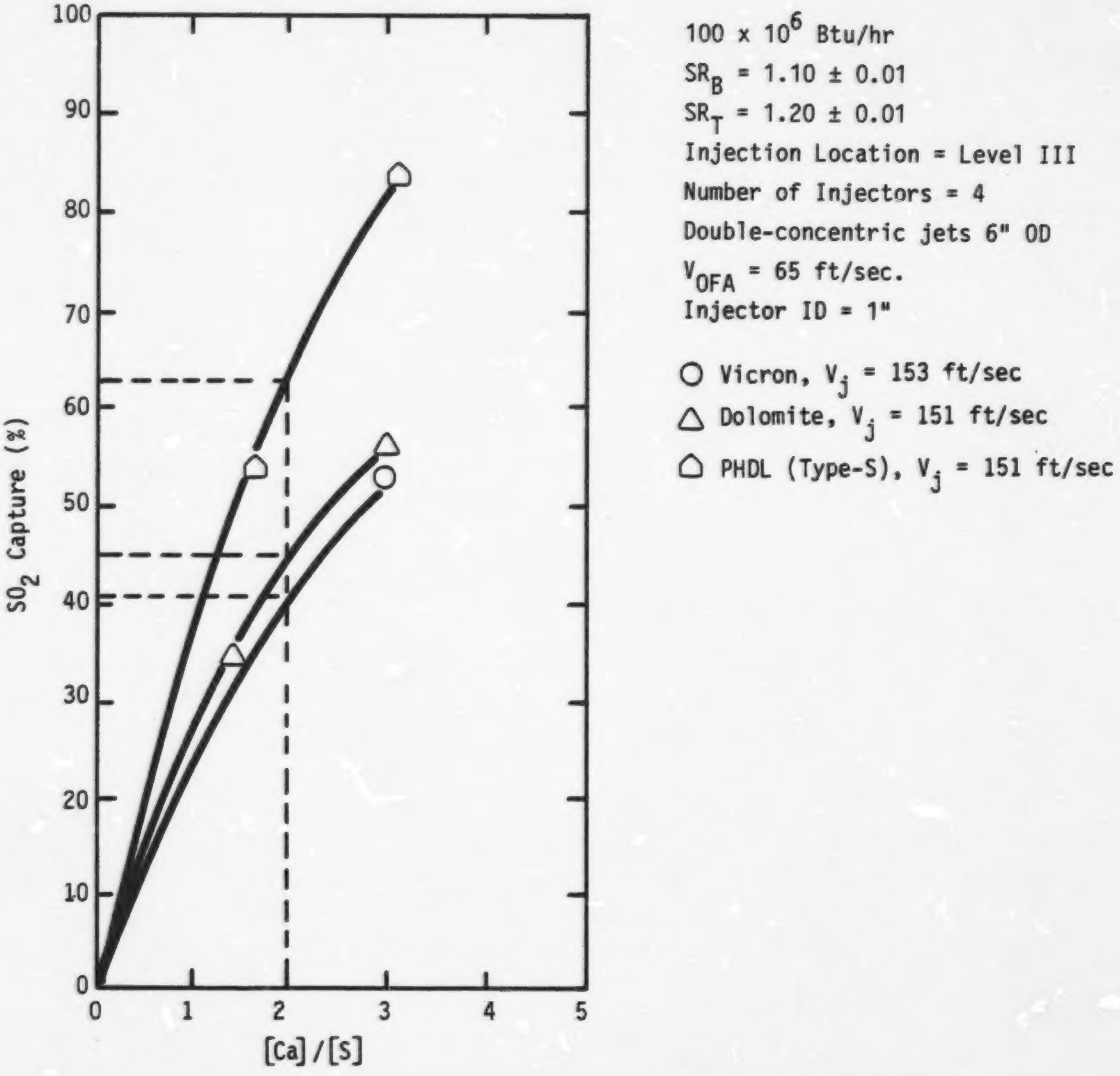


Figure 3-25. SO$_2$ capture by sorbents injected into the upper furnace through double-concentric jets on the front wall (Level III).

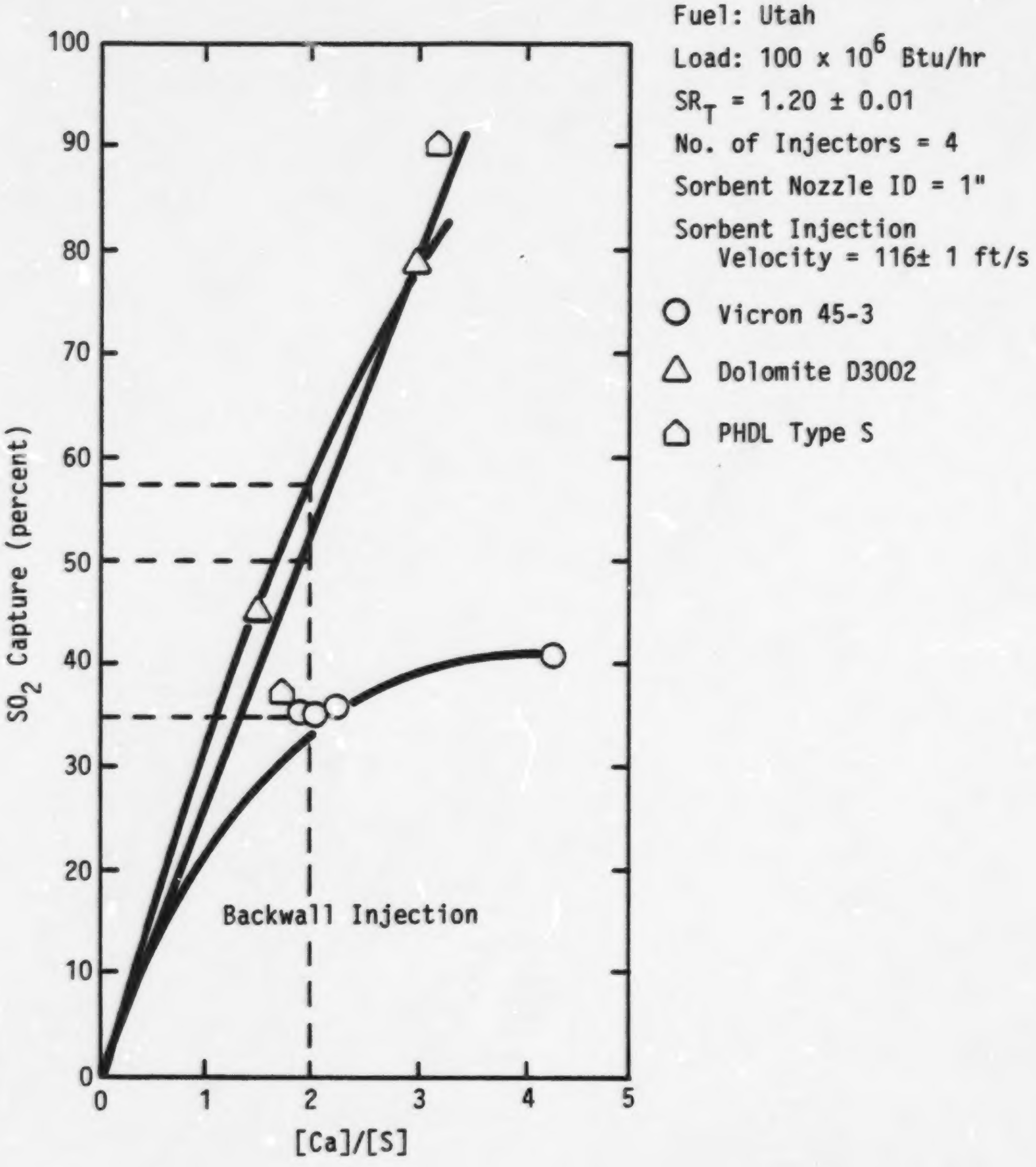


Figure 3-26. SO_2 capture by sorbents injected into the upper furnace through single-pipe injectors located on the furnace back wall.

4.0 CONCLUSIONS FROM LWS SORBENT INJECTION STUDIES

This testing on the 100 x 10^6 Btu/hr Large Watertube Simulator had the objective of investigating combined SO_2/NO_x reduction in a pilot-scale simulation of a utility boiler using an internally-staged low-NO_x burner combined with SO_2 sorbent injection in the upper furnace region. The emphasis was on the effect of sorbent injection configurations on overall SO_2 capture. In addition, limited optimization of the burner was undertaken for NO_x reduction.

The burner optimization studies showed some potential for NO_x reduction with the particular internally-staged burner tested here (the IS-100 burner). The intent of the internally-staged burner is to achieve NO_x reductions without the external tertiary air ports characteristic of commercial low-NO_x burners, and to achieve the internal fuel/air staging with high burner velocities (to facilitate retrofit into existing pre-NSPS boilers without extensive modifications to increase the size of the burner opening in the firing wall). The baseline unstaged burner tested here with the annular coal nozzle (a typical pre-NSPS burner configuration) gave NO_x emissions in the range 830-900 ppm (dry, 0% O_2), typical of pre-NSPS burners. Significant reductions were achieved with the staged IS-100 burner using axial coal nozzles employing the T-15 or T-30 coal splitters. These splitters produced reductions in NO_x of about 150-200 ppm. The optimum configuration in these tests was with the T-30 coal nozzle and the low swirl register setting. This configuration gave 550 ppm NO_x (dry, 0% O_2), with an acceptable flame length of 22 feet, and CO less than 40 ppm. The NO_x reductions achieved were limited in part because -- due to the emphasis on the SO_2 portion of this project -- the full range of internal staging options was not investigated (e.g., divided secondary air registers were not employed in the IS-100 burner).

Sorbent injection from the front wall of the furnace gave unexpectedly poor SO_2 capture; better sorbent performance would have been anticipated, considering that the gas temperatures at the injection points were near optimum. Cold-flow physical modelling showed that this the poor capture was caused by a strong recirculation zone above the burner which extended into the upper furnace region. This zone created a down-flow of furnace gas along the front wall, which drew the sorbent into the flame. The bulk of the gas flow to the furnace exit took the form of a relatively thin layer of gas, about 2 feet thick, flowing up the rear wall. In view of this flow pattern, sorbent injection from the rear wall appeared to be an attractive approach, because of the low risk of the injected sorbent being carried into the flame.

Sorbent injection from the rear wall gave reasonable SO_2 capture, reaching 35 percent capture at Ca/S = 2 for Vicron 45-3 limestone (10 microns mass mean). Capture was very sensitive to sorbent injection velocity, because it was necessary to match the jet penetration to the thickness of the gas flow up the rear wall. If injection velocity was too high, sorbent penetrated across the thin exit flow layer into the recirculation zone, and was carried down into the flame zone. If the injection velocity was too low, the sorbent was not adequately dispersed in the up-flow stream.

Reasonable SO_2 capture was also obtained from front wall injection in the upper furnace region, 19 feet above the burner. However, good front-wall performance could be achieved only with large-diameter, high-velocity jets. These jets had sufficient momentum to penetrate across the recirculation zone and carry most of the sorbent into the exiting flue gas flow. With four 6-inch diameter jets at and an injection velocity of 70 ft/s, the SO_2 capture by Vicron at Ca/S = 2 was 30 percent. Capture was improved when the jets were configured in a double-concentric mode, with the sorbent injected in a 1-inch diameter jet along the axis of the larger (6-inch diameter) annular air jet. Apparently, this allowed a greater fraction of the sorbent to reach the exit gas flow without being drawn down into the flame zone. The capture increased as the sorbent jet velocity was increased, consistent with results observed with double-concentric jet tests in the earlier, smaller-scale testing (Reference 1). The reason for this effect is not clear, but it is thought to be related to changes in mixing conditions in the jet. Capture during front-wall injection was also greater with a larger number of jets (4 instead of 2), probably because, with four jets, the two outer-most jets near the sides of the furnace were delivering sorbent to a region where the recirculation down-flow into the burner zone was not so strong. The best capture achieved with the double-concentric jets was about 40 percent at Ca/S = 2 for Vicron limestone.

Tests were conducted using D3002 dolomite and Type S pressure-hydrated dolomitic lime, as well as Vicron limestone, for the best front- and rear-wall injection configurations. The dolomitic sorbents gave superior capture to the limestone. Dolomite gave SO_2 capture in the range 45 to 50 percent at Ca/ S = 2, and the pressure hydrate gave capture in the range 58 to 62 percent. The relative performance of these three sorbents (dolomitic hydrate better than raw dolomite better than limestone) is similar to results that have been observed in other experimental investigations, such as Reference 1.

5.0 REFERENCES

1. Cetegen, B. M., J. Clough, G. C. England, T. R. Johnson, Y. Kwan, and R. Payne, "Evaluation of Internally Staged Coal Burners and Sorbent Jet Aerodynamics for Combined SO_2/NO_x Control in Utility Boilers. Volume 1 - Testing in a 10 Million Btu/hr Experimental Furnace," EPA-600/7-89-007, June 1989 (NTIS No. PB89-207955).

2. Patrick, M. A., "Experimental Investigation of Mixing and Flow in a Round Turbulent Jet Injected Perpendicularly into a Main Stream," Journal of the Institute of Fuel, September 1967, pp. 425-431.

3. Thring, M. B., and M. P. Newby, "Combustion Length of Enclosed Turbulent Jet Flames," Fourth Symposium on Combustion, The Combustion Institute, 1953.

APPENDIX A

QUALITY ASSURANCE: LWS SORBENT INJECTION TESTS

Quality Assurance Objectives

The collection and analysis of quality data is key to the success of this program. Procedures outlined in the Quality Assurance Plan (QAPP), submitted prior to beginning actual testing, were followed to ensure data quality. Specific Quality Assurance (QA) program objectives are outlined in Table A-1. These objectives were based on the the program requirement and the precision and accuracy levels achievable by the selected measurement methods. Table A-2 lists the sampling procedures for each measurement. The procedures are standard EPA, ASTM, or other recognized methods. The following QA procedures utilized during this program are divided into daily routing and system verification checks:

Daily Routine

- Air Flow Distribution
- Air Preheat and Combustor Wall Temperature
- Gas Phase Species--Continuous Monitoring
- Pretest Oil Check
- Fuel Size Distribution
- Particulate Samples
- Time Limitation of Valid Data

System Verification

- Venturi Flowmeter Calibrations
- Instrument Performance Tests

The incorporation of the QA procedures into the test plan, ensured the documentation and collection of quality data resulting in verifiable and more accurate result and conclusions.

TABLE A-1. PROGRAM OBJECTIVES FOR MEASUREMENT PRECISION, ACCURACY, AND COMPLETENESS.

Parameters	Measurement Methods	Reference	Precision: Relative Standard Deviation (%)	Accuracy (%)	Completeness (%)
Burner Settings	Direct Inspection		10	10	90
Air Distribution	Calibrated Venturi Flowmeter		4	5	90
Air Flow Rate and Distribution	Thermocouples		5	5	90
Fuel Flow Rate	Weigh Belt Feeder		4	10	90
Combustor Wall Temperature	Thermocouples		5	5	90
NO/NO_x	Continuous Monitor Chemiluminescence	EPA Performance Specification 2	2	20	90
CO	Continuous Monitor NDIR		2	20	90
CO_2	Continuous Monitor NDIR	EPA Performance Specification 3	2	20	90
SO_2	Continuous Monitor UV	EPA Performance Specification 2	2	20	90
O_2	Continuous Monitor (Paramagnetic)	EPA Performance Specification 3	2	20	90
SO_3	Controlled Condensation	Process Meas Proc EPA 68-02-2165, 2/77	20	20	80
Particulate Mass Loading	EPA Method 5		12	20	70
Particulate Size Distribution	X-Ray Sedimentation		20	20	80
Solid Composition	Ultimate and Proximate Analyses (ASTM)	ASTM	5	5	90
Fuel Size Distribution	ASTM Method	ASTM D197	10	10	80
Flame Characteristics	Color Video and Direct Inspection		Qualitative	Qualitative	75
Sorbent Feed Rate	Volumetric Feeder		10	10	90
Windbox Pressure	Magnehelic-Bourdon Tube		10	10	90

TABLE A-2. SAMPLING PROCEDURES

Parameters	Measurement Methods	Sampling Location Selection Criteria	Sampling Procedure	Sampling Frequency	Reference
Burner Settings	Direct Inspection	Burners	Direct Inspection	Every Test Condition	
Air Flow Rate and Distribution	Calibrated Venturi Flowmeter	Air Inlet Ducts		Every Test Condition	
Air Preheat Temperature	Thermocouples	Burner		Every Test Condition	
Fuel Flow Rate	Weigh Belt Feeder	Upstream of Pulverizer	Continuous Direct Weight	Every Test Condition	
Combustor Wall Temperature	Thermocouples	Selected Locations in Furnace		Every Test Condition	
NO/NO_x	Continuous Monitor Chemiluminescence	Modified EPA Performance Specifications for Continuous Monitors	Extractive (See Text)	Continuous	Fed Register Vol 44 No 197 Oct 10, 1979 pp 58602-58636
CO	Continuous Monitor NDIR				
CO_2	Continuous Monitor NDIR				
SO_2	Continuous Monitor UV				
O_2	Continuous Monitor (Paramagnetic)				
SO_3	Controlled Condensation	EPA Process Measurement Procedures		Selected Conditions	
Particulate Mass Loading	EPA Method 5	EPA Level 1 Solid Sampling Procedures	Extractive	Selected Conditions	Fed Register Vol 42 No 160 Aug 18, 1977 pp 41776-41782
Particulate Size Distribution	X-Ray Sedimentation				
Solid Composition	Ultimate and Proximate Analyses (ASTM)		Grab Sample	Daily	EPA 600/7-78-201 p 105
Fuel Size Distribution	ASTM Method	ASTM D197	Multipoint Grab Sample	Daily	ASTM D197
Flame Characteristics	Color Video and Direct Inspection	Furnace Sample Ports		Every Test Condition	
Sorbent Feed Rate	Volumetric Feeder			Every Test Condition	
Windbox Pressure	Magnehelic-Bourdon Tube			Every Test Condition	

Table A-3 summarizes the precision and accuracy results of the system measurements as determined in accordance with the QAAP. For each of the measurements, the results are within the limits established in the program goal except the O_2 analyzer. The oil check is an additional QA procedure used by EER to determine the overall precision and accuracy of the complete facility measurement system including air and fuel flowrates, temperature, and emission monitors. The oil check is discussed in detail in Section A.1. Instrument precision is determined from repeat calibrations throughout the entire test series. The following subsections discuss each of the QA procedures for the specific measurements.

A.1 Daily Routine Procedures

Routine calibrations and checks were performed on a daily basis to ensure that test data would be accurate, representative, and reproducible. Daily calibration included air flow indication and flue gas analyzers. Other daily checks included verification of thermocouple operation, system oxygen balance while firing oil igniter, pulverized coal size distribution, and time averaged valid data.

A.1.1 Air Flow Distribution

The distribution of combustion air between the burner passages was determined by direct measurement of the air flow rate to each passage using 18-inch venturi flowmeters. Each venturi was calibrated immediately prior to each test series using a standard pitot tube. During testing, the pressure drop of the air through each venturi was continuously monitored using low pressure electronic transducers. Each transducer was calibrated manually prior to and immediately after testing each day at pressure differentials of 0-in. and approximately 3-in. H_2O. The calibrations are documented daily as shown in Table A-4 for a representative test day. The response from the transducers was calibrated within their linear range such that 1.0 v response = 2.0-in H_2O pressure differential. From the calibrations, the precision and accuracy of the air flow measurements. Table A-5 summarizes

TABLE A-3. SUMMARY OF PRECISION AND ACCURACY

Measurement	Precision (%)		Accuracy (%)	
	Actual	Goal	Actual	Goal
Air Distribution	1.0260	4	1.872	10
Oil Check	3.1700	-	2.830	--
NO/NO_x	0.4320	≤ 2	11.540	≤ 20
CO_2	0.1405	≤ 2	8.767	≤ 20
CO	0.6850	≤ 2	--	≤ 20
SO_2	0.2917	≤ 2	17.620	≤ 20
O_2	0.4800	≤ 2	34.130	≤ 20

TABLE A-4. TYPICAL VENTURI FLOWMETER PRESSURE TRANSDUCER CALIBRATION

DATE: 1-24-85 FACILITY: LWS. PROJECT: IS, LWS

TRANSDUCER/ VENTURI	247 ZERO		756 SPAN		1809 ZERO		1806 SPAN		ZERO		SPAN		ZERO		SPAN	
	ΔP	MV	ΔP	MV	ΔP	MV	ΔP	MV	ΔP	MV	ΔP	MV	ΔP	MV	ΔP	M
1	0.0	.001	4.7	2.372	0.0	001	3.6	1.795								
2		.002		2.374		004		1800								
3		.000		2.374		002		1.796								
4		.002		2.378		001		1802								
5		.001		2.379		005		1802								
6		-.001		2.380		+001		1815								
7		–														
8		–														
9	0.0	-.001	4.7	2.371	0.0	.004	3.6	1.780								
10																

TABLE A-5. DETERMINATION OF CALIBRATION DRIFT OF PRESSURE TRANSDUCERS FOR AIR FLOWRATE CALCULATION

	Value
Initial Zero	1.4515 MV
Zero Error	7.53 ± 7.2236 MV
Zero Precision	0.4897 %
Confidence Coefficient (Zero)	4.59 MV
Zero Drift	0.8217 %
Initial Calibration[1]	1475 MV
Calibration Error	26.496 ± 23.88 MV
Calibration Precision	1.026 %
Confidence Coefficient (Calibration)	17.084 MV
Calibration Drift	1.872 %

[1] Reference Δp using inclined manometer

the zero and calibration drift of the transducers during the test. The zero drift was 0.82 percent and the calibration drift was 1.87 percent.

A.1.2 Air Preheat and Combustor Wall Temperatures

Type K (Chromel/Alumel) thermocouples were used to monitor the combustion air and furnace wall temperatures. ASTM Standard E231-77 specifies that the standard limit of error for Type K commercial thermocouples be ± 2°C or ± 0.75 percent between 0° and 1250°. To assure that the thermocouples were functioning during testing, a continuous output of the temperatures was displayed on the computer data acquisition printout. In case of thermocouple malfunction, the damaged TC was immediately replaced. If, due to location restrictions, it was not practical to replace the TC while testing, it was replaced prior to the next day of testing.

A.1.3 Gas Phase Species

The exhaust gas phase species composition was measured using the LWS laboratory sampling system as outlined in Figure A-1. Flue gas was sampled immediately upstream of the LWS system SO_x and particulate scrubber ensuring that the flue gas sample was representative of the furnace effluent. A single sample probe which draws from the center of the duct was used. All materials in contact with the sample gas are limited to glass, stainless steel, Teflon, and a small amount of Kel-F (valve seals) since these materials have been demonstrated as essentially nonreactive to the gases measured over the temperature range involved in this system.

This system is generally satisfactory for most tests, but may result in SO_2 sorbents, such as limestone, are present. Therefore, an independent SO_2 sample system, described in Section , was utilized. The critical temperatures of the SO_2 sample system were maintained and recorded in a daily log. Table A-6 shows an example of the daily test log of temperatures and sample flows. The filter may also introduce an error in SO_2 concentration measured during sorbent injection due to agglomeration of particles on the filter, thus creating a scrubbing effect independent of the injection

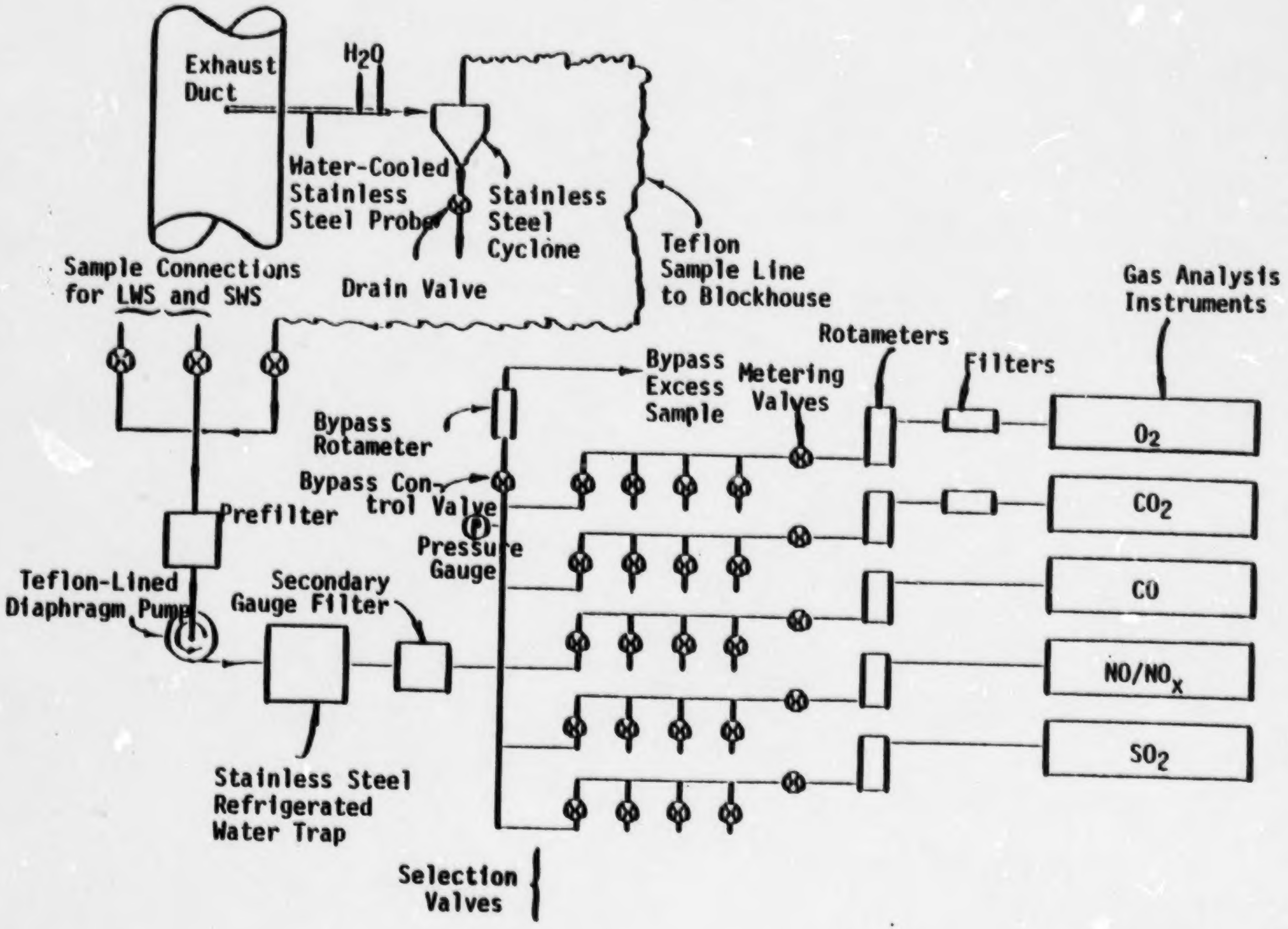

Exhaust Duct
H_2O
Water-Cooled Stainless Steel Probe
Stainless Steel Cyclone
Drain Valve
Teflon Sample Line to Blockhouse
Sample Connections for LWS and SWS
Gas Analysis Instruments
Rotameters
Filters
Bypass Excess Sample
Metering Valves
Bypass Rotameter
Bypass Control Valve
Pressure Gauge
Prefilter
Teflon-Lined Diaphragm Pump
Secondary Gauge Filter
Stainless Steel Refrigerated Water Trap
Selection Valves
O_2
CO_2
CO
NO/NO_x
SO_2

Figure A-1. LWS sample train.

TABLE A-6. TYPICAL SO_2 SAMPLE SYSTEM QA LOG

QUALITY & A LOG DUPONT: SO_2 SAMPLE DATE: 1-22-85

TIME	SAMPLE		ZERO		HIGH SPAN		LOW SPAN		SAMPLE		DRYER	CELL °F	OVEN °F	HEATED LINE °F	VARIAC	NEW AIR INITIAL
	CELL PRES	ROTO	CELL	ROTO	CELL	ROTO	CELL	ROTO	CELL	ROTO						
0930			.65	4.0			.65	4.0			40	100	[illegible]	[illegible]	100	
10:00			.65	4.0			.65	4.0			40	110	[illegible]	[illegible]	100	
11:00			.65	4.0			.65	4.0			40	114	[illegible]	[illegible]	100	
1130			.65	4.0			.65	4.0			40	94	[illegible]	178	100	
1210			.65	4.0			.65	4.0			40	104	221	180	100	
1300			0.8	4.0			0.8	4.0	0.7	4.0	40	108	225	169	100	
14:40			0.8	4.0			0.8	4.0	0.7	4.0	40	109	218	193	100	FH
15[illegible]			0.7	4.0			0.7	4.0	0.7	4.0	40	94	2[illegible]0	204	100	
1643			0.7	4.0			0.7	4.0	0.7	4.0	40	94	246	191	100	

parameters. Therefore, this filter was changed at least after every two tests of sorbent injection had been completed or as necessary to maintain a clean filter. During sorbent testing, baseline test points (with no sorbent) were taken immediately preceding sorbent injection. After the sorbent test was completed, the system was allowed to return to baseline before continuing with sorbent injection. Therefore, the relative SO_2 concentrations of the preceding and past test baseline should remain constant, therefore assuring that no measured SO_2 loss was occurring during sorbent injection because of any scrubbing effects of the sample system.

Table A-7 lists the continuous gas analyzers used during these tests. To ensure accuracy, the instruments are operated according to EPA Performance Standards 2 and 3. Each instrument was calibrated with three certified gases; a zero gas and two span gases, at approximately 50 and 90 percent of scale. To increase accuracy and precision, the instruments were calibrated approximately every two hours during the test day. The instrument calibrations included electronically calibrating the instrument response to the data logger and the strip chart recorder, simultaneously. This ensured that the instrument, computer printout, and the strip chart were in agreement. The calibrations were documented in a calibration log, such as the example shown as Table A-8, as well as the computer printout and strip chart. This log provided data to evaluate the calibration drift of each instrument for each day of testing. Generally, if the calibration drift exceeded 4 percent during a calibration interval, the valid data obtained during that period was corrected for drift.

A.1.4 Pretest Oil Check

A pretest oil check was completed daily, prior to switching the system to coal. The oil check is used to warm up the system and as a QA check on the overall LWS process system. The oil check is a ratio between the calculated and measured load. The calculated load is a theoretical determination based on the heating value of the fuel oil and the measured oil flow rate. It is independent of the air flow system. The measured load is a function of the O_2 concentration measured in the exhaust, and the air and

TABLE A-7. CONTINUOUS GAS ANALYZERS

Gas Measured	Type of Instrument	Manufacturer	Model No.	Range
O_2	Paramagnetic	Beckman	755	10 percent
CO_2	Nondispersive Infrared (NDIR)	Anarad, Inc.	AR 500 R	20 percent
CO	Nondispersive Infrared (NDIR)	Anarad, Inc.	AR 500 R	500 ppm
NO_x	Chemiluminescent	Thermo Electron Corp.	10 AR	1000 ppm
SO_2	Long Path Nondispersive Ultraviolet (NDUV)	DuPont	400	5000 ppm

TABLE A-8. TYPICAL DAILY INSTRUMENT CALIBRATION

DATE: 1-25-85 FACILITY: LWS PROJECT: IS/LWS

TIME:	1004	1209	1350	1554		1730	
O_2							
INITIAL ZERO (Zi)-DIV/MV	0.0	0.0	0.0	0.0			
INITIAL SPAN (Si)-DIV/MV	90.0	93.0	90	90.0			
FINAL ZERO (Zf)-DIV.		0.0	0.0	0.0		0.0	
FINAL SPAN (Sf)-DIV.		90.0	90.0	90.0		88.2	
SPAN GAS (Gs) P/0/DIV.	9.03						
ZERO DRIFT (%) - $\frac{Z_i-Z_f}{G_s}$							
SPAN DRIFT (%) - $\frac{S_i-S_f}{G_s}$							
CO_2							
INITIAL ZERO (Zi)-DIV/MV	0.0	+.4	0.0	0.0			
INITIAL SPAN (Si)-DIV/MV	50.0	49.5	50.0	50.0			
FINAL ZERO (Zf)-DIV.			0.0	0.0		0.0	
FINAL SPAN (Sf)-DIV.			50.0	50.0		50.0	
SPAN GAS (Gs)-%/DIV.	10.0						
ZERO DRIFT (%) - $\frac{Z_i-Z_f}{G_s}$							
SPAN DRIFT (%) $\frac{S_i-S_f}{G_s}$							
CO							
INITIAL ZERO (Zi)-DIV/MV	0.0	+.7	0.0	0.0			
INITIAL SPAN (Si)-DIV/MV	50.0	49.0	50.0	50.0			
FINAL ZERO (Zf)-DIV.		0.0	0.0	0.0		0.0	
FINAL SPAN (Sf)-DIV.		50.0	50.0	50.0		50.0	
SPAN GAS (Gs)-PPM/DIV.	252						
ZERO DRIFT (%) - $\frac{Z_i-Z_f}{G_s}$							
SPAN DRIFT (%) - $\frac{S_i-S_f}{G_s}$							
NO_x							
INITIAL ZERO (Zi)-DIV/MV	0.0	+.7	0.0	0.0			
INITIAL SPAN (Si)-DIV/MV	81.7	81.2	81.7	81.7			
FINAL ZERO (Zf)-DIV.		0.0	0.0	0.0		0.0	
FINAL SPAN (Sf)-DIV.		81.7	81.7	81.7		81.5	
SPAN GAS (Gs)-PPM/DIV.	817						
ZERO DRIFT (%) - $\frac{Z_i-Z_f}{G_s}$							
SPAN DRIFT (%) - $\frac{S_i-S_f}{G_s}$							
SO_2			1305	1350	520	1615	6:15
INITIAL ZERO (Zi)-DIV/MV		0.0	-1.5	0.0	-3.0	-1.0	.7
INITIAL SPAN (Si)-DIV/MV		79.8	79.8	79.8	79.8	79.8	79/
FINAL ZERO (Zf)-DIV.			0.0		0.0		
FINAL SPAN (Sf)-DIV.			79.8		79.8		
SPAN GAS (Gs)-PPM/DIV.		79.8					
ZERO DRIFT (%) - $\frac{Z_i-Z_f}{G_s}$							
SPAN DRIFT (%) - S_i-S_f							

fuel flow rates. The resultant ratio indicates the overall accuracy of the measurement system: transducers, continuous monitoring instruments, temperatures, and fuel flow rate. The difference between the calculated and measured load had to be less than 10 percent in order to proceed with testing.

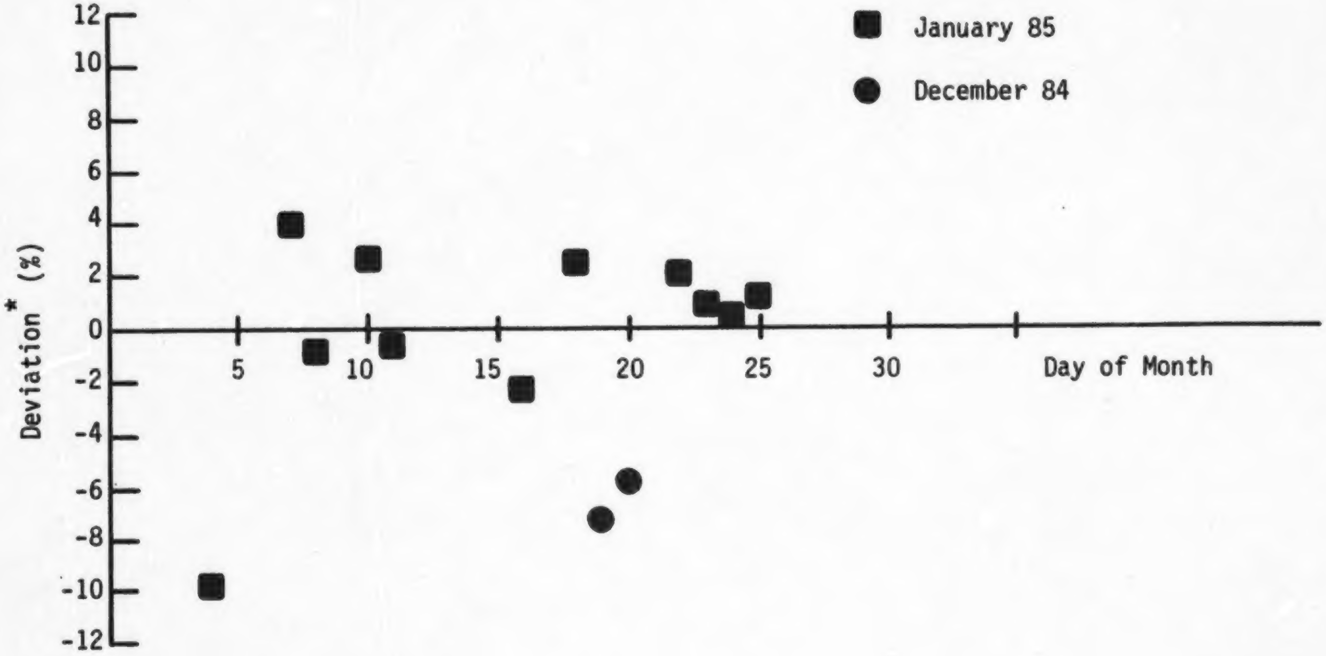
Figure A-2 shows the daily plots of the oil checks obtained throughout the test. This plot shows the relative trend of the overall system. Table A-9 summarizes the accuracy and precision of the measurement system as determined by the oil check for the test. The accuracy was <3 percent with precision <4 percent which are well below the program objectives of 10 percent.

TABLE A-9. SUMMARY OF ACCURACY AND PRECISION OF MEASUREMENT SYSTEM AS DETERMINED BY OIL CHECKS

Test Phase	Accuracy (%)	Precision (%)
IS-100	2.83	3.17

A.1.5 Fuel Size Distribution

The coal fineness affects the combustion performance of the burner; therefore, it was necessary to determine the coal fineness daily. The coal sample was drawn isokinetically according to the procedures as outlined in ASTM Method D197 and the ASME Performance Test Code for Coal Pulverizers. The coal sample probe is shown in Figure A-3. An isokinetic sample is drawn by a vertical and horizontal traverse of the coal pipe at a sample location downstream of the pulverizer. A sample was taken daily for each coal type and firing rate. The recovery rate as specified by the method must be 100 percent ± 10 percent. After each sample the recovery rate was calculated. Table A-10 shows an example of the recovery rate during the tests. If the recovery rate was not within the limits, another sample was taken if



$$^{*}\text{Deviation} = \left[\frac{\text{Measured Load - Calculated Load}}{\text{Calculated Load}}\right] \times 100$$

Figure A-2. Oil check summary.

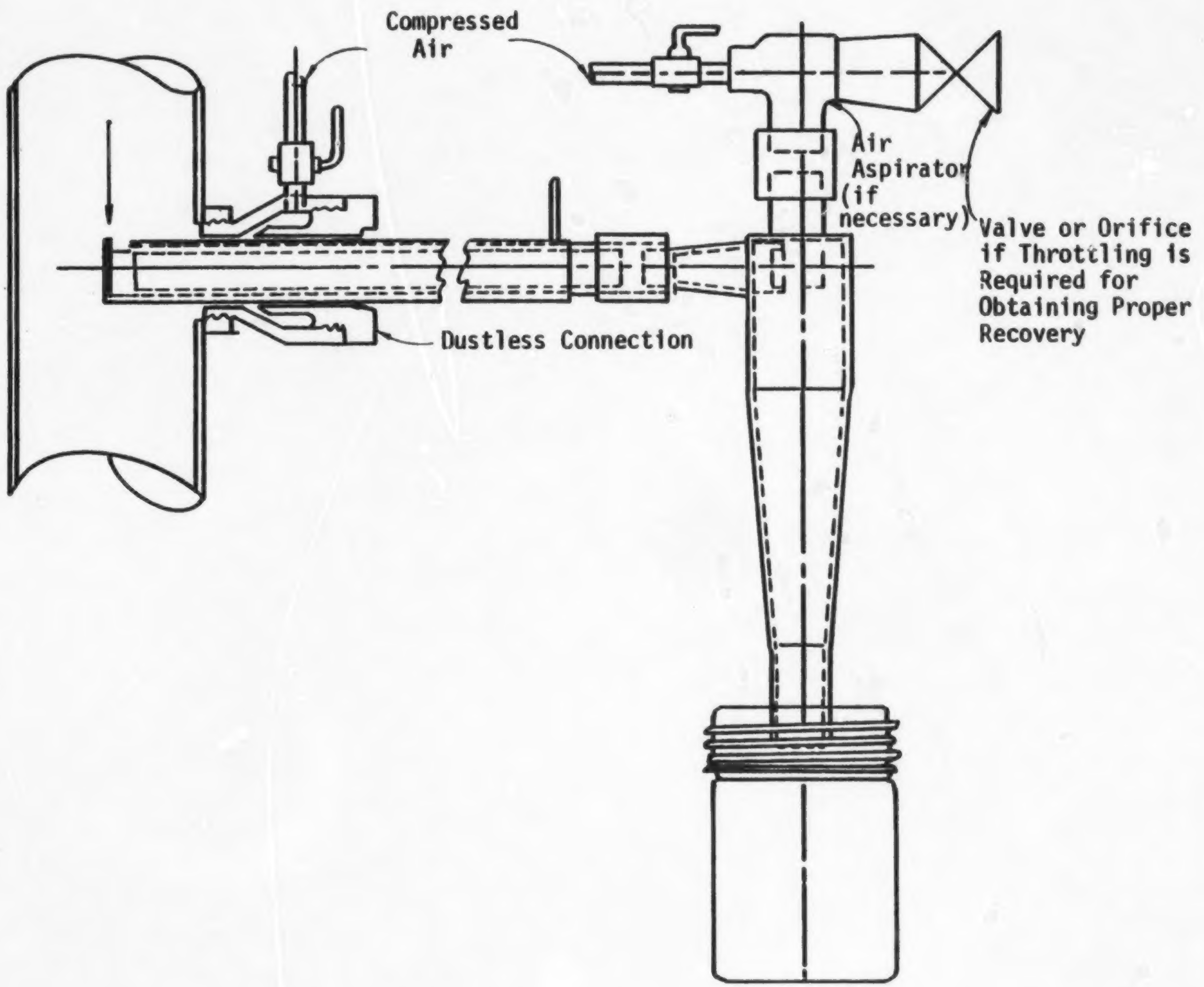

Compressed Air
Air Aspirator (if necessary)
Valve or Orifice if Throttling is Required for Obtaining Proper Recovery
Dustless Connection

Figure A-3. Pulverized coal sampling system.

TABLE A-10. TYPICAL CALCULATION OF COAL FINENESS RECOVERY RATE

PROJECT IS-700/LWS FACILITY LWS

COAL FINENESS RECOVERY RATE

				BURNER FLOWRATE						SAMPLE FLOWRATE						
DATE	FUEL	TIME	SAMPLE NO.	Known Load (lbs/h)	CALCULATED LOAD (x10⁶ Btu/h)	CALCULATED COAL FLOW (lbs/h)	COAL FLOW (lbs/min)	COAL PIPE AREA (in²)	BURNER COAL FLOWRATE (lbs/min/in²)	COAL COLLECTED (gms)	SAMPLE TIME (min)	SAMPLE COAL FLOWRATE (lbs/min)	NOZZLE AREA (in²)	SAMPLE COAL FLOWRATE (lbs/min/in²)	RECOVERY RATE (%)	SAMPLER R4: [illegible]
12/19	UTAH	1230	112128	6800	101.8	7571.58	126.19	153.86	0.8202	193.14	2	0.2129	0.305	0.698	85.1	
12/20	UTAH	1020	112153	6900	100.8	7497.2	124.95		0.8121	209.31	2	0.2307		0.7565	93.15	
1/4/85	UTAH	1040	112155	7700	95.75	7121	118.7		0.7714	219.03	2	0.2414		0.7916	102.62	
1/8/85	UTAH	1201		7300	94.10	6999	116.65		0.7581	257.39	2	0.2837		0.9302	122.7	
1/8/85	" "	1224	112182	7200	96.727	7194.3	119.85		0.7793	202.82	2	0.2236		0.7330	94.06	
1/11/85	" "	1036	112223	7500	98.75	7344.7	122.41		0.7956	198.78	2	0.2191		0.7189	90.50	

COAL FINENESS SIZE ANALYSIS

DATE	TIME	SAMPLE NO.	JAR TARE (gms)	TOTAL NET WEIGHT (gms)										COAL NET WT (START) (gms)	NET WT >200 mesh (gms)	% L 200 mesh
12/19	1230	112128	41.47	234.61										14.66	3.48	76.3
1/4	10:18	112155	41.62	260.65										14.90	4.08	72.6

operating conditions allowed. After verifying a recovery rate of 100 ± 10 percent, the sample was analyzed for size distribution.

A.1.6 Valid Data Acquisition

The outputs of all continuous instrumentation (flow rates, temperatures, and emissions) are converted to electrical signals, put into digital notation, and supplied to a Hewlett Packard computer. The computer processes this data and provides a real-time indication of input and output parameters. As a QA procedure, during a given test condition, valid data points yield average inputs and outputs, by manually inputting the gaseous concentrations. In addition, temperatures and flow rates are corrected if required to ensure that the results of the specific test includes only valid data and conditions.

A.2 System Verification Procedures

During this test program, system verification procedures that were performed included venturi flowmeter calibrations and instrument performance tests. The accuracy and precision of both air flow and the concentrations of exhaust gas components are essential to achieving quality data.

A.2.1 Venturi Flowmeter Calibration and Leak Checks

Calibrations of the venturi flowmeter were performed prior to the start of testing. The relationship between the air flow rate and pressure drop across the venturi can be expressed as:

$$Q = K \left(\frac{\Delta\rho}{T}\right)^{1/2} \qquad \text{(A-1)}$$

where: Q = mass flowrate through the venturi (scfm)

$\Delta\rho$ = pressure drop across the venturi (in H_2O)

T = absolute air temperature (^oR)

K = calibration constant

Calibrations were conducted for each venturi over a range of air flow rates, with the data reduced to the form of equation (A-1). These calibrations were incorporated into the data acquisition program used for this program. Records of the calibrations are maintained at EER.

The air flow rates measured by the venturis in the LWS system are remotely monitored. Pressure taps and thermocouples are mounted on each venturi, with the pneumatic tubing and thermocouple lead wire run into the LWS control room. Because of the environment of heat and moisture surrounding the venturis during testing, leak checks of the pneumatic tubing from the venturi to pressure transducers in the control room are conducted periodically during the test program.

A.2.2 Instrument Performance Tests

The LWS continuous monitoring system is operated according to EPA Specification 2 and 3. These specifications include instrument performance test guidelines. As part of the QA plan for this test series, an abbreviated instrument performance test was conducted. Table A-11 summarizes the results for both test series.

The relative accuracy was determined by comparing the instrument values to values obtained using EPA Reference Methods. There is currently no performance specification for the CO monitor or standard reference method for CO determination. Therefore, relative accuracy for CO could not be determined, but the 2-hour drift test was conducted in accordance with the guidelines for the other analyzers. The results show that the relative accuracy for the SO_2, CO_2, and NO_x instruments were within EPA specifications. The relative accuracy of the Beckman O_2 analyzer was not within the specifications. The result is biased by a large error in 3 of the 23 method-7 samples where air leaks into the sample flasks were suspected. The relative accuracy for the Beckman O_2 analyzer in previous tests was normally found to be less than 10 percent.

TABLE A-11. INSTRUMENT PERFORMANCE TESTS SUMMARY

Instrument Manufacturer	Relative Accuracy (%)	EPA Specification	Calibration Error %		EPA Specification	2-Hour Drift Test			
			Mid	High		Zero Drift (%)	EPA Specification (%)	Calibration Drift (%)	EPA Specification (%)
O_2 Beckman	34.13*	≤20	1.23	0.840	≤5	0.0133	≤0.4	0.0815	≤0.4
CO_2 Anarad	8.767	≤20	0.271	2.082	≤5	0.0488	≤0.4	0.3595	≤0.4
NO_x, TECO	11.54	≤20	2.308	0.603	≤5	0.346	≤2.0	0.6920	≤2.0
CO, Anarad	--	--	3.30	0.930	--	0.434	--	1.230	--
SO_2, Dupont	17.62	≤20	0.516	0.657	≤5	1.569	≤2.0	1.7907	≤2.0

* Air Leakage in Sample Flasks

The O_2, CO_2, NO_x, and SO_2 instruments are within the specifications for zero and calibration drift. The calibration error determines the linearity of the instruments. For each of the instruments, the linearity is within acceptable limits established in the EPA specifications.

APPENDIX B

REDUCED DATA: LWS SORBENT INJECTION TESTS

APPENDIX B

REDUCED DATA: LWS SORBENT INJECTION TESTS

	Burner Configuration				Injectors			Operating Conditions								Emissions				
													Sorbent						SO2	
Test #	Coal Nozzle Type	Splitter Position (inches)	Swirl Setting (degree)	# of OFA Ports	No. of Injectors	Sorbent Injector I.D.(in.)	Sorbent Injection Location	Load (10^6 Btu/hr)	SR_P (%)	SR_B (%)	SR_T (%)	Core air (scfm)	Type	Ca/S	Injection velocity (ft/s)	O_2 (%)	CO (ppm)	NO_x (ppm)	(ppm)	Capture (%)
Test Series 0 -- Baseline NO_x Testing with Unstaged Burner (no sorbent)																				
0-1	Annular	0	50	0	0	--	--	101.1	18	121	121	422	--	--	--	3.7	36	825	492	--
0-2	↓	↓	38	↓	↓	--	--	101.8	19	121	121	419	--	--	--	3.8	37	855	525	--
0-3	↓	↓	15	↓	↓	--	--	99.0	18	119	119	408	--	--	--	3.5	36	912	504	--
0-4	↓	↓	50	↓	↓	--	--	102.6	17	119	119	369	--	--	--	3.4	36	805	501	--
0-5	↓	↓	50	↓	↓	--	--	99.4	18	120	120	675	--	--	--	3.6	36	869	519	--
0-6	↓	↓	50	↓	↓	--	--	99.1	18	121	121	727	--	--	--	3.7	36	825	473	--
Test Series 1 -- NO_x Testing with IS-100 Burner, T-15 Splitter (no sorbent)																				
1-01	T-15	+2	38	0	0	--	--	99.2	19	120	120	--	--	--	--	3.6	36	591	471	--
1-02	↓	+2	15	↓	↓	--	--	98.2	18	119	119	--	--	--	--	3.4	36	752	--	--
1-03	↓	+2	50	↓	↓	--	--	98.6	20	121	121	--	--	--	--	3.7	30	619	--	--
1-04	↓	+2	38	↓	↓	--	--	97.2	18	121	121	--	--	--	--	3.8	37	684	--	--
1-05	↓	+2	50	↓	↓	--	--	98.4	18	130	130	--	--	--	--	5.0	39	748	459	--
1-06	↓	+7	50	↓	↓	--	--	98.6	18	119	119	--	--	--	--	3.5	36	672	492	--
1-07	↓	+14	50	↓	↓	--	--	99.0	18	120	120	--	--	--	--	3.6	36	712	531	--
Test Series 2 -- SO_2 and NO_x Testing with IS-100 Burner, T-30 Splitter																				
2-01	T-30	+2	50	0	0	--	--	99.6	18	120	120	--	--	--	--	3.6	36	597	507	--
2-02	↓	↓	38	↓	0	--	--	99.8	18	119	119	--	--	--	--	3.5	36	660	540	--
2-03	↓	↓	15	↓	0	--	--	96.8	18	121	121	--	--	--	--	3.8	37	769	476	--
2-04	↓	↓	50	↓	0	--	--	100.5	18	120	120	--	--	--	--	3.6	36	628	519	--
2-05	↓	↓	50	↓	4 (angle out)	1	Tubes in 2° channel)	98.9	17	119	119	--	MW125*	4.07	166	3.5	36	612	348	16.32
2-06	↓	↓	↓	↓	"	1	"	100.1	19	120	120	--	--	--	--	3.6	36	603	507	--
2-07	↓	↓	↓	↓	"	1	"	102.9	17	119	119	--	--	--	--	3.5	36	636	540	--
2-08	↓	↓	↓	↓	"	1	"	103.5	17	118	118	--	MW125	1.96	166	3.3	36	617	475	10.80
2-09	↓	↓	↓	↓	"	1	"	101.0	18	120	120	--	--	--	--	3.6	36	640	525	--
2-10	↓	↓	↓	↓	2 (angle in)	1	"	101.3	18	120	120	--	MW125	1.96	332	3.6	36	634	471	9.25
2-11	↓	↓	↓	↓	"	1	"	101.7	18	119	119	--	--	--	--	3.4	36	632	513	--
2-12	↓	↓	↓	↓	"	1	"	100.3	18	121	121	--	MW125	1.98	165	3.8	37	659	446	13.31
2-13	↓	↓	↓	↓	4 (angle out)	1	"	101.1	18	119	119	--	--	--	--	3.5	36	636	516	--
2-14	↓	↓	↓	↓	"	1	"	99.8	18	121	121	--	Vicron	1.99	166	3.7	36	668	407	20.45
2-15					"	1	"	99.6	17	120	120	--	--	--	--	3.6	36	664	507	--

APPENDIX B (continued)

	Burner Configuration				Injectors			Operating Conditions								Emissions				
													Sorbent						SO_2	
Test #	Coal Nozzle Type	Splitter Position (inches)	Swirl Setting (degree)	# of OFA Ports	No. of Injectors	Sorbent Injector I.D.(in.)	Sorbent Injection Location	Load (10^6 Btu/hr)	SR_P (%)	SR_B (%)	SR_T (%)	OFA veloc. (ft/s)	Type	Ca/S	Injection velocity (ft/s)	O_2 (%)	CO (ppm)	NO_x (ppm)	(ppm)	Capture (%)
2-16	T-30	+2	50	0	0	--	--	98.7	17	121	121	0	--	--	--	3.8	37	610	454	--
2-17					4 (angle in)	1	Tubes in 2^o channel	98.7	17	120	120		--	--	--	3.6	36	603	507	--
2-18					•	1	•	100.8	18	119	119		Vicron	1.71	166	3.5	36	594	384	22.42
2-19					•	1	•	99.9	18	120	120		--	--	--	3.6	36	603	483	--
2-20					•	1	•	99.5	18	119	119		MW125	1.97	166	3.5	36	600	420	17.57
2-21					•	1	•	99.4	18	119	119		--	--	--	3.4	36	626	537	--
2-22					1	--	Pre-mixed with coal	100.1	18	119	119		MW125	2.0	82	3.5	36	636	456	11.88
2-23					0	--	--	101.1	18	118	118		--	--	--	3.3	36	617	498	--
2-24					1	--	Pre-mixed with coal	100.1	18	119	119		Vicron	1.99	83	3.5	36	612	408	16.22
2-25					0	--	--	96.8	19	123	123		--	--	--	4.0	37	618	476	--
2-26				4	4	6	Level III	99.2	18	116	121	29	--	--	--	3.8	37	549	464	--
2-27					4	6	•	99.7	18	116	121	31	Vicron	1.5	36	3.8	37	562	391	16.09
2-28					4	6	•	101.7	18	113	119	33	--	--	--	3.5	36	564	468	--
2-29					4	6	•	102.0	18	113	119	32	--	--	--	3.4	36	561	525	--
2-30					4	6	•	102.0	18	113	119	30	Vicron	2.96	35	3.4	36	561	394	24.95
2-31					4	6	•	100.7	18	115	121	33	Vicron	1.51	38	3.7	36	571	413	13.33
2-32					4	6	•	102.2	18	113	119	35	--	--	--	3.5	36	588	480	--
2-33					4	6	•	101.3	18	114	120	32	D3002	3.29	37	3.6	36	603	338	31.09
2-34					4	6	•	100.7	18	114	120	33	D3002	2.99	38	3.6	36	591	362	26.20
2-35					4	6	•	99.5	18	115	121	34	--	--	--	3.8	37	598	501	--
2-36					4	6	•	98.6	18	117	121	19	--	--	--	3.7	36	589	510	--
2-37					4	6	•	98.6	18	116	119	13	Vicron	3.23	18	3.4	36	573	406	17.40
2-38					4	6	•	98.6	18	109	121	64	Vicron	2.94	69	3.7	36	522	304	38.15
2-39					4	6	•	99.3	18	110	121	61	--	--	--	3.7	36	522	473	--
2-40					4	6	•	99.7	18	115	121	29	Vicron	3.26	34	3.7	36	595	364	24.72
2-41					4	6	•	98.0	19	119	123	21	--	--	--	4.0	37	605	494	--
2-42					4	6	•	100.5	18	108	121	75	--	--	--	3.7	49	425	510	--
2-43					4	6	•	99.1	18	108	121	73	Vicron	2.83	78	3.7	49	449	358	29.78
2-44				0	2	1	Level IV	96.8	18	121	121	0	--	--	--	3.7	36	571	528	--
2-45					2	1	•	99.0	18	120	120	0	Vicron	2.78	162	3.6	36	579	435	17.38
2-46					2	1	•	98.6	18	121	121		--	--	--	3.8	37	586	525	--
2-47					2	1	•	101.2	17	118	118		Vicron	1.61	162	3.3	36	570	445	15.24
2-48					2	1	•	100.9	18	119	119		--	--	--	3.4	36	585	525	--
2-49					2	2.5	Level II	100.7	18	119	119		Vicron	1.50	59	3.4	36	597	453	14.45
2-50					2	2.5	•	99.1	18	121	121		--	--	--	3.7	36	607	534	--
2-51					2	2.5	•	100.7	17	119	119		Vicron	3.0	59	3.4	36	621	424	20.15
2-52					2	2.5	•	99.5	18	119	119		--	--	--	3.5	36	624	528	--
2-53					2	2.5	•	99.5	18	119	119		--	--	--	3.5	36	636	384	--
2-54					0	--	--	100.6	18	118	118		--	--	--	3.3	36	593	558	--

APPENDIX B (continued)

	Burner Configuration				Injectors			Operating Conditions								Emissions				
													Sorbent						SO_2	
Test #	Coal Nozzle Type	Splitter Position (inches)	Swirl Setting (degree)	# of OFA Ports	No. of Injectors	Sorbent Injector I.D.(in.)	Sorbent Injection Location	Load (10^6 Btu/hr)	SR_P (%)	SR_B (%)	SR_T (%)	OFA veloc. (ft/s)	Type	Ca/S	Injection velocity (ft/s)	O_2 (%)	CO (ppm)	NO_x (ppm)	(ppm)	Capture (%)
2-55	T-30	+2	50	0	4	1	Level III	100.0	17	118	118	0	Vicron	2.86	162	3.3	36	623	392	29.62
2-56						--	"	--	--	--	--		--	--	--	--	--	--	--	--
2-57					2	1	Level IV	100.7	18	119	119		--	--	--	3.5	36	708	--	--
2-58					2	1	"	100.0	17	119	119		Vicron	2.08	253	3.5	36	702	432	20.66
2-59					2	1	"	99.8	18	120	120		--	--	--	3.6	36	712	513	--
2-60					2	1	"	101.9	17	119	119		Vicron	2.19	162	3.4	36	709	459	11.30
2-61					2	1	"	101.6	17	118	118		--	--	--	3.3	36	700	522	--
2-62					2	1	"	96.7	18	125	125		Vicron	1.33	106	4.3	38	755	396	25.0
2-63					2	1	Level III (center 2)	102.8	17	119	119		Vicron	2.26	243	3.5	36	720	414	21.5
2-64					2	1	"	101.1	18	121	121		--	--	--	3.7	36	765	534	--
2-65					2	1	"	101.5	17	120	120		Vicron	2.21	162	3.6	36	724	447	14.86
2-66					2	1	"	102.1	17	119	119		--	--	--	3.5	36	738	516	--
2-67					2	1	Level II	100.8	17	120	120		Vicron	2.37	243	3.6	36	736	435	16.67
2-68					2	1	"	103.0	17	118	118		Vicron	1.93	162	3.3	36	700	445	14.75
2-69					2	1	"	102.5	18	119	119		--	--	--	3.5	36	708	528	--
2-70					4	1	Back wall	98.1	19	120	120		--	--	--	3.6	36	664	543	--
2-71					4	1	"	97.7	18	120	120		Vicron	2.34	151	3.6	36	664	422	21.85
2-72					4	1	"	97.1	19	121	121		--	--	--	3.8	37	672	537	--
2-73					4	1	"	98.5	18	118	118		Vicron	2.20	140	3.3	36	653	439	17.56
2-74					4	1	"	95.8	19	121	121		--	--	--	3.7	36	680	529	--
2-75					4	1	"	103.3	18	119	119		Vicron	1.96	115	3.4	36	621	340	35.61
2-76					4	1	"	102.3	17	119	119		Vicron	2.07	80	3.4	36	621	376	28.79
2-77					4	1	"	101.2	18	119	119		--	--	--	3.5	36	648	528	--
2-78					4	1	"	94.8	18	120	120		Vicron	2.30	115	3.6	36	640	338	35.98
2-79					4	1	"	102.0	18	119	119		Vicron	4.31	115	3.5	36	684	312	40.91
2-80					2	1	Back wall (center 2)	98.5	16	119	119		--	--	--	3.5	36	660	528	--
2-81					2	1	"	100.3	18	121	121		Vicron	1.87	177	3.7	36	680	455	13.83
2-82					2	1	"	100.2	18	121	121		--	--	--	3.7	36	656	546	--
2-83					2	1	"	98.0	18	123	123		Vicron	1.38	125	4.0	37	655	476	10.86
2-84					2	1	"	99.8	18	121	121		--	--	--	3.7	36	643	522	--
2-85					4	1	Back wall	100.8	18	119	119		Vicron	2.07	118	3.4	36	597	382	27.45
2-86					4	1	"	99.6	18	120	120		--	--	--	3.6	36	591	531	--
2-87					4	1	"	101.0	19	119	119		PHDL	3.22	114	3.5	36	660	120	77.27
2-88					4	1	"	101.9	19	119	119		--	--	--	3.4	36	632	525	--
2-89					4	1	"	100.8	19	120	120		PHDL	3.19	121	3.6	36	640	54	89.22
2-90					4	1	"	101.7	18	119	119		--	--	--	3.4	36	644	477	--
2-91					4	1	"	101.3	19	120	120		--	--	--	3.6	36	640	561	--
2-92					4	1	"	99.9	18	119	119		PHDL	1.74	118	3.5	36	648	348	36.96
2-93					4	1	"	100.0	19	120	120		--	--	--	3.6	36	628	543	--
2-94					4	1	"	98.7	19	121	121		D3002	3.03	119	3.8	43	653	122	77.47
2-95					4	1	"	100.9	19	119	119		--	--	--	3.5	42	624	540	--

APPENDIX B (continued)

	Burner Configuration				Injectors			Operating Conditions					Sorbent			Emissions			SO2	
Test #	Coal Nozzle Type	Splitter Position (inches)	Swirl Setting (degree)	# of OFA Ports	No. of Injectors	Sorbent Injector I.D.(in.)	Sorbent Injection Location	Load (10^6 Btu/hr)	SR_P (%)	SR_B (%)	SR_T (%)	OFA veloc. (ft/s)	Type	Ca/S	Injection velocity (ft/s)	O_2 (%)	CO (ppm)	NO_x (ppm)	(ppm)	Capture (%)
2-96	T-30	+2	50	0	4	1	Back wall	101.8	19	119	119	0	D3002	1.47	118	3.4	42	626	298	45.27
2-97					4	1	•	99.5	19	121	121		--	--	--	3.8	37	659	549	--
2-98					4	1	•	101.0	19	119	119		Vicron	2.09	114	3.5	36	636	348	35.73
2-99					4	1	•	100.2	19	121	121		--	--	--	3.7	36	631	534	--
2-100					4	1	Level III	99.7	19	121	121		Vicron	2.13	151	3.7	36	637	407	22.70
2-101					4	1	•	100.2	19	120	120		Vicron	2.21	82	3.6	42	634	410	22.13
2-102				↓	4	1	•	101.3	18	119	119	↓	--	--	--	3.4	36	632	519	--
2-103				4	4	1	Level III (dbl conc)	101.9	18	109	120	64	--	--	--	3.6	54	567	531	--
2-104					4	1	•	101.2	18	109	120	64	Vicron	3.07	153	3.6	60	567	226	52.73
2-105					4	1	•	101.2	18	109	121	66	--	--	--	3.7	49	546	473	--
2-106					4	1	•	102.4	17	107	119	67	--	--	--	3.4	42	561	549	--
2-107					2	1	Level III (outer 2)	101.7	17	108	119	66	Vicron	2.01	160	3.5	36	558	384	29.02
2-108			↓	↓	2	1	•	102.3	18	108	119	67	--	--	--	3.5	42	576	534	--
2-109			30	0	2	2.5	Level I	60.7	32	121	121	0	--	--	--	3.7	49	443	510	--
2-110					2	2.5	•	59.5	33	121	121		Colton	1.94	54	3.8	49	440	317	39.96
2-111					2	2.5	•	60.0	33	121	121		--	--	--	3.7	55	425	546	--
2-112					2	2.5	•	60.5	33	120	120		Vicron	3.51	54	3.6	48	416	260	51.72
2-113					2	2.5	•	60.1	33	121	121		Vicron	1.99	54	3.7	43	425	334	37.98
2-114					2	2.5	•	60.6	33	120	120		--	--	--	3.6	42	410	531	--
2-115					2	2.5	Level II	59.8	30	121	121		--	--	--	3.8	39	452	525	--
2-116					2	2.5	•	60.2	31	121	121		Colton	1.97	56	3.8	43	464	317	40.3
2-117					2	2.5	•	60.3	31	121	121		--	--	--	3.8	37	452	537	--
2-118					2	2.5	•	60.0	30	121	121		Colton	5.12	56	3.8	37	452	226	57.91
2-119					2	2.5	•	60.6	30	121	121		Colton	3.01	56	3.7	36	449	255	52.51
2-120					2	2.5	•	60.2	30	121	121		Vicron	1.40	56	3.8	37	452	385	28.31
2-121					2	2.5	•	60.2	30	121	121		--	--	--	3.8	37	452	537	--
2-122					2	2.5	•	59.8	31	121	121		Vicron	2.95	56	3.7	43	437	340	37.56
2-123			↓	↓	2	2.5	•	60.0	31	121	121	↓	--	--	--	3.7	43	437	552	--
2-124			50	4	4	1	Level III (dbl conc)	101.8	19	110	122	67	--	--	--	3.9	43	467	540	--
2-125					4	1	•	101.8	18	109	121	66	Vicron	1.69	118	3.8	43	464	379	32.38
2-126					4	1	•	101.6	19	110	123	67	--	--	--	4.0	43	469	581	--
2-127					4	1	•	101.1	18	109	121	65	Vicron	3.13	118	3.8	37	464	354	38.75
2-128					4	1	•	98.6	19	112	124	65	--	--	--	4.2	38	463	575	--
2-129					2	1	Level III (2 outer)	100.1	18	112	124	64	Vicron	3.03	122	4.2	38	513	413	28.17
2-130					2	1	•	101.2	19	111	123	63	Vicron	2.01	124	4.0	37	494	457	20.52
2-131					4	1	Level III (all 4)	101.1	18	108	120	69	--	--	--	3.6	36	459	543	--
2-132					4	1	•	99.0	18	108	120	65	D3002	1.41	151	3.6	36	471	350	34.82
2-133	↓	↓	↓	↓	4	1	•	98.8	18	109	120	64	--	--	--	3.6	36	507	531	--

APPENDIX B (continued)

	Burner Configuration				Injectors			Operating Conditions								Emissions				
													Sorbent						SO$_2$	
Test #	Coal Nozzle Type	Splitter Position (inches)	Swirl Setting (degree)	# of OFA Ports	No. of Injectors	Sorbent Injector I.D.(in.)	Sorbent Injection Location	Load (10^6 Btu/hr)	SR$_P$ (%)	SR$_B$ (%)	SR$_T$ (%)	OFA veloc. (ft/s)	Type	Ca/S	Injection velocity (ft/s)	O$_2$ (%)	CO (ppm)	NO$_x$ (ppm)	(ppm)	Capture (%)
2-134	T-30	+2	50	4	4	1	Level III	100.6	18	109	118	66	D3002	3.05	151	3.3	36	439	237	56.71
2-135	↓	↓	↓	↓	4	1	•	99.6	18	108	119	65	D3002	3.22	81	3.5	42	504	264	51.78
2-136	↓	↓	↓	↓	4	1	•	99.9	18	109	119	62	--	--	--	3.5	36	516	564	--
2-137	↓	↓	↓	↓	4	1	•	101.5	18	109	120	61	D3002	1.46	81	3.6	36	507	362	32.96
2-138	↓	↓	↓	↓	4	1	•	100.1	18	111	122	60	--	--	--	3.9	37	552	516	--
2-139	↓	↓	↓	↓	4	1	•	101.6	18	109	120	63	PHDL	1.64	81	3.6	36	519	193	63.45
2-140	↓	↓	↓	↓	4	1	•	102.4	18	108	119	63	--	--	--	3.5	36	516	540	--
2-141	↓	↓	↓	↓	4	1	•	101.5	18	109	121	63	PHDL	3.54	81	3.7	36	528	212	58.63
2-142	↓	↓	↓	↓	4	1	•	101.8	18	109	121	63	--	--	--	3.7	36	510	486	--
2-143	↓	↓	↓	↓	4	1	•	101.4	18	109	120	64	PHDL	1.57	81	3.6	36	507	296	43.40
2-144	↓	↓	↓	↓	4	1	•	100.6	18	108	119	65	PHDL	1.68	151	3.5	36	516	240	54.11
2-145	↓	↓	↓	↓	4	1	•	102.2	18	107	118	65	PHDL	3.14	151	3.3	42	498	83	84.13
2-146	↓	↓	↓	↓	4	1	•	102.1	18	108	119	66	--	--	--	3.4	36	525	561	--

Notes:

* Three primary sorbents were tested: Vicron 45-3 limestone ($CaCO_3$); D3002 dolomite ($CaCO_3/MgCO_3$); and Type-S pressure-hydrated dolomitic lime [$Ca(OH)_2/Mg(OH)_2$], referred to in the above table as PHDL. Limited testing was also conducted with: Marblewhite limestone, a less finely-ground version of Vicron (referred to in the table as MW125); and Colton calcitic lime [$Ca(OH)_2$], hydrated at atmospheric pressure.

The concentrations of CO, NO_x and SO_2 in this table are corrected to dry conditions and 0% O_2.